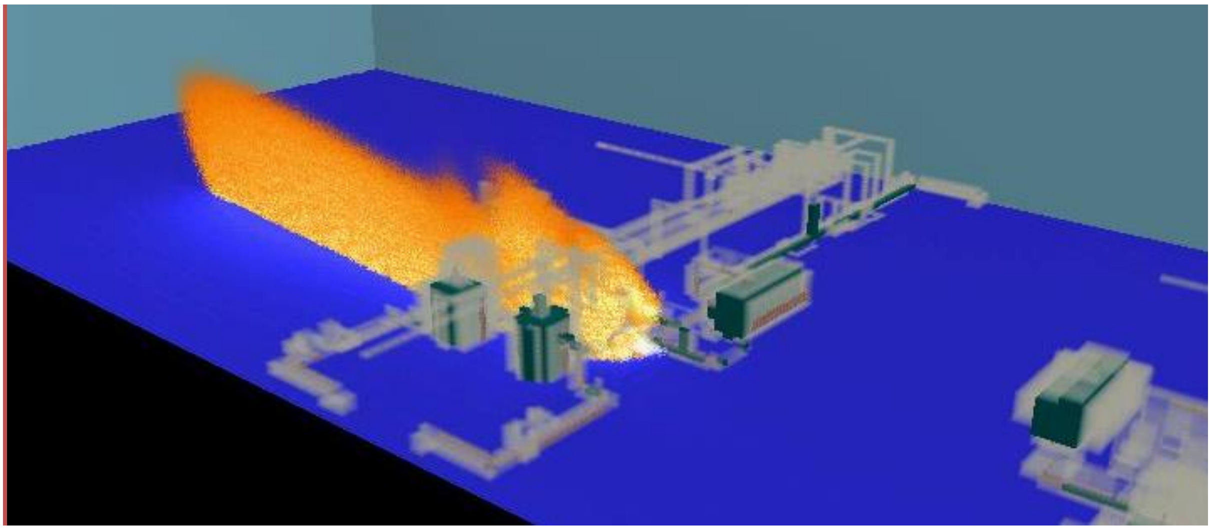
Scenario based analysis of fire escalation in a gas process plant



Master degree project conducted at
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Master degree thesis

Students name: Joachim Søreng Bjørge

Line & study Process safety and safety technology/ technical safety

Report title: *Scenario based analysis of fire escalation in a gas process plant*

Problem description:
The thesis will focus on a medium-sized gas processing plant, - "reference plant". There will be concrete and specific descriptions of the plant. Some previous studies are *carried out for Reference plant, as the risk analysis will be available. The assignment will be based on a limited number - (*4 -6 *small and medium sized*) *realistic leaks from various segments in the system.*

1. *For each scenario shall the further progress be described, including gas dispersion, ignition, fire and if likely fire escalation when rupture occurs on exposed pressurized equipment. This will be carried out with the exemption that the barriers established for the plant functions as intended.*
2. *Based on the knowledge that is established; identify measures / instruments that are expected to reduce the risk of escalation of fire - a major accident.*
3. *For each identified measure: describe the effect of the measure in an appropriate manner.*

Submission date: Friday 3.june 2013 kl. 15.00

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Classification Open

Approved by program coordinator: Terje Finnekås

Date: 07.05.2012

Preface

This master thesis ends my 2 years of education within technical safety at HSH/UIB, and in total 5 years of higher education.

The problem description of the thesis did change throughout the year. For example; ignition and gas dispersion was in some degree downgraded, and the main focus became effect of blowdown and escalation. Writing a thesis of this magnitude is a learning process, and my levels of knowledge have obviously changed. This and some new areas of interest for me and my supervisors are the main reasons for the changes.

It is when the thesis is finished, and you get everything at a certain distance, that you clearly see the result. I feel that this thesis have brought to life some new questions that are of interest to me and others. I trust that some questions are answered, and some new knowledge is gained, so that I can give something back to those who have helped me and supported me through the process.

I would like to thank my 4 supervisors; Gudmundur Kristjansson and Odd Johannes Tveit at Gassco and Svein Jacob Nesheim and Bjarne Paulsen Husted at HSH. You have opened my eyes to a new world within technical safety and computing, and I am truly grateful. Furthermore, I would like to thank Bjørn Erling Vembe for all your help and discussion around KFX and simulations in general. In addition I am grateful to Geir Berge for taking me in and making me part of your work environment. You have both given me an insight that will undoubtedly prove useful in the future.

Jens Kristian Holen and Roy Andre Midtgård, I am also most grateful for your guidance and discussions.

Summary

This study takes place on a medium sized gas process plant called reference plant. In this thesis several escalation scenarios, as well as gas dispersion, is evaluated through Kameleon KFX and Vessfire.

It has previously been conducted similar escalation studies. However, a normal approach to conduct these studies is to use reference values of a uniform property for heat flux both global and peak, and will only record/evaluate if rupture occurs.

In this thesis uses every scenario transient curves for leak flow in KFX to represent the leak (jet fire). From these results individual values for heat flux, both peak and global, is found and used in Vessfire as heat flux exposure on process segment, to evaluate escalation and effect of blowdown. The effect of use of insulation, increased blowdown flow to vent stack and increased wall thickness is also evaluated in this thesis.

How a jet fire develops could in some cases be dependent on the geometry of the process site. This is a factor that could get lost when using standardized values for exposure by fire (ref NORSOK S-001).

The results indicates that pressurized pipes with the given properties for carbon steel and utilization as used in reference plant (pipes in the range of 2 and 3 inch of diameter) is expected to rupture, when exposed to heat flux over 300 kW/m^2 over a time period of 2 to 3 minutes.

With the restriction value for flow in the blowdown system today and an increase in flow of 50%, blowdown alone will not prevent rupture of smaller pipe diameters when exposed as described above. However an increase in depressurization flow and a sequential blowdown philosophy, combined with early activation time for initiation of blowdown is proven to minimize the risk of escalation from one process train to another.

When a jet fire passes objects the heat flux could increase on the other side as a result of increased turbulence.

When a jet fire is directed into larger objects, the location of hot spots (peak flux values) on pipes and nearby equipment will not vary significantly, with time and strength in the release for the chosen scenarios. The values for global and peak flux will actually in some cases be almost constant. Objects can work as flame stabilizers. However, when the jet is unaffected by objects the hot spots could move over larger distances as the release flow decreases.

Terminology and Definitions

Some of the terminology used in the report is listed below.

Active fire Protection:	Equipment, system and methods which, following initiation may be used to control, mitigate or extinguish fires [10].
Barrier:	Measure that reduce the probability for a hazard with a high damage potential to be realized, and if it works reduce the potential consequence of the event [2].
Consequence:	A measure of the expected effects of an accidental event [3].
Corrosion allowance:	Wall thickness reduced due to corrosion. Factor used in Vessfire, applies only to carbon steel pipes and equipment.
Depressurization:	Controlled reduction of pressure by disposal of fluids to a disposal system (flare or vent system), also called blowdown [10].
Fire:	A process of combustion characterized by heat or smoke or flame or an combination of these [3].
Fire load:	Load experienced by humans or structure as a result of a fire [3].
Flare system:	System consisting of pipes from the flow orifice connected to process segments and knock-out drum, leading to the flare stack for safe disposal.
Flow orifice:	Restricting device for flow from the segment to the flare system [9].
Global heat load:	Heat load exposing whole pipes, vessels or segments. Used for pressure profile calculation [16].
Hazard:	Possibility for personal injury, damage on the environment, damage on property or a combination of these [2].
Hazardous area:	Three-dimensional space in which a flammable atmosphere may be expected to be present at such frequencies as to require precautions for the control of potential ignition sources [1].
Incident radiation heat flux:	The gross radiation heat flux exposing an object. Normally, only a fraction of the incident radiation flux will be absorbed by the object [10].

Incident heat flux:	The gross radiation heat flux + the convective heat flux to an object at ambient temperature [10].
Jet fire:	Fire resulting from release of pressurized gas and/or liquid [3].
Local peak heat load:	Heat load exposing only parts of pipes, vessels or segments. Used for rupture calculation.
Process segment:	All equipment and piping within 1 depressurization volume. The ESD or PSD valves connected to the segment define the battery limit of the depressurization volume. The process segment is depressurized through the BDV and depressurization orifice. A single pressurized vessel, storage or transportation tank etc. can also be defined as a process segment [10].
Risk:	A measure of economic loss, human injury or environmental pollution in terms of both the incident likelihood and the magnitude of the loss or injury [3].
Risk analysis:	A qualitative or quantitative estimate of risk based on engineering evaluation and mathematical techniques combining consequence and frequencies [3].
Risk Acceptance criteria:	Criteria used to express a risk level which is considered to be acceptable for the actual activity, limited to express risk at high level [7].
Segment:	The depressurization volume, a section of the total processing system, consisting of pipes, valves, vessel and other equipment. Segregated from the rest of the processing system by sectioning valves (XV or HV).
Stress & Strain:	Stress is the internal force that affects the material within while strain is the ratio of deformation on the outside.
Ultimate stress:	The highest point on the stress strain curve for a given material at a given temperature (maximum stress the material can withstand before necking).
Yield strength:	Point on the stress strain curve for a given material at a given temperature where the material begins to deform.

Abbreviations

Abbreviations used in the report are given in this section.

AFP	Active Fire Protection
ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute (standards)
BD	Blowdown
BDV	Blowdown Valve or Depressurization Valve
CFD	Computational Fluid Dynamics
DAL	Dimensioning Accidental Load
EDC	Eddy Dissipation Concept
ESD	Emergency Shut Down
FO	Flow Orifice
FVM	Finite Volume Method
ISO	International Organization for Standardization
KFX	Kameleon KFX
LEL	Lower Explosive Limit
LVS	Landfall Valve Station
MIE	Minimum Ignition Energy
NORSOK	NORsk SOkkels Konkurranseposisjon
PFP	Passive Fire Protection
PSD	Pressure Safety Valve
PSV	Pressure Control Valve
RP	Recommended Practice
UEL	Upper Explosive Limit
UTS	Ultimate Tensile Strength

Contents

1. Introduction

The following section includes some background for the thesis, a short description of the work scope/process and a brief overview of the report.

1.1 Background for the thesis

Fire is a threat that is difficult to predict as it is not an unambiguous phenomenon, but a result of many random circumstances. To solve these complex phenomena there is used acknowledged simulation tools and standardized values for exposure by fire. Using these tools and standard values for exposure will the result always be conservative? And what will the simplifications be? Wrong design could in some cases result in a higher cost then necessary, and maybe not work as intended against hazards.

If a fire threatens the process site and, the operator has to depressurize the exposed segment. Can they expect the fire to escalate and does the blowdown procedure occur in the most effective way?

The study takes place on a medium sized gas process plant, called reference plant which was built in the late 1980/early 90. The terminal has had no major upgrades on the process system since its construction. However, in its later years there have been some minor improvements, as increasing the blowdown/shutdown orifice area to increase the mass flow to the vent and some upgrades in the control and monitoring system. This assignment will focus on the process site.

1.2 Problem definition

The thesis will be based on a limited number (small and medium sized) realistic transient leaks from various segments in the system.

1) For each scenario shall the further progress be described, including gas dispersion, fire and if likely fire escalation when rupture occurs on exposed pressurized equipment. This will be carried out with the exemption that the barriers established for the plant functions as intended.
2) Based on the knowledge that is established; identify measures / instruments that are expected to reduce the risk of escalation of fire - a major accident.
3) For each identified measure: describe the effect of the measure in an appropriate manner.

The area of concern is escalation and effect of blowdown, ignition and ignition probability is therefore not evaluated.

1.3 Scope of work

This thesis is divided into three parts (ref, Problem description), whereas number two and three both concerns the use and effect of risk reducing measures. Number one is about the issue of fire escalation and gas dispersion in a medium sized gas process plant. Where different leakage scenarios will be defined from high pressure equipment/parts and some ignited allowing a jet fire to be formed, and further evaluate the jet`s effect on surrounding pipes and equipment. A risk analysis executed in 2007 is used as guidance in defining the leak scenarios.

Two simulation tools will be used in this thesis Kameleon KFX and Vessfire. Kameleon KFX is used to find properties of incoming heat flux on objects, duration, strength of the jet and to evaluate gas dispersion. The information from KFX will further be implemented into Vessfire to measure the effect on exposed pipes and segments and to evaluate escalation, effect and capacity of the blowdown system.

The simulation process is divided into three phases:

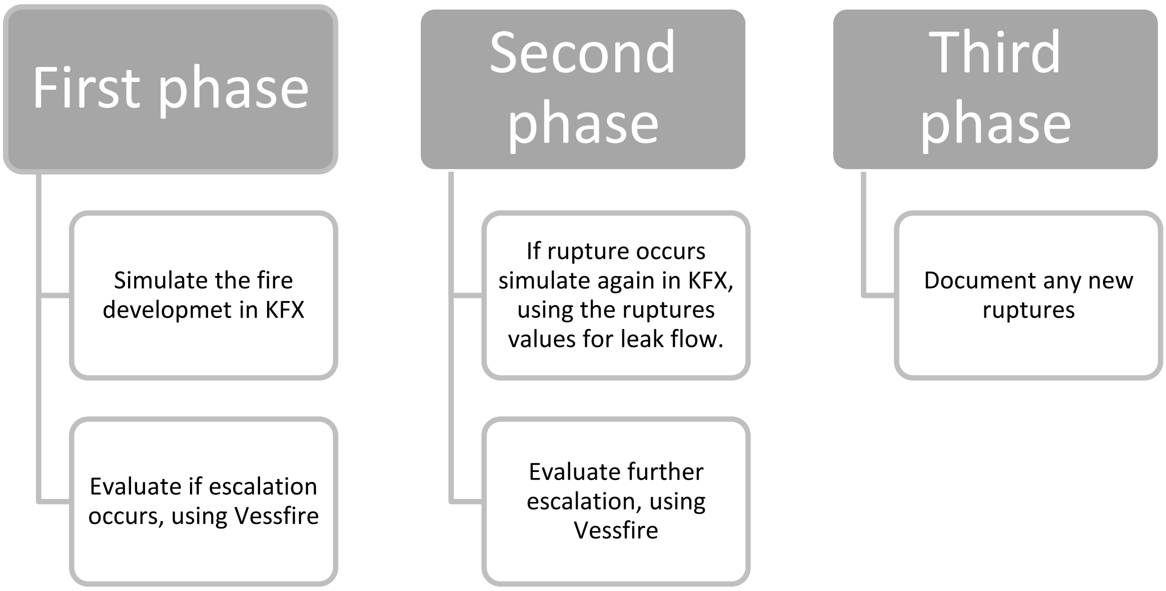


Figure 1 Explanation of the 3 phases.

1) Find the values for net heat flux on objects in KFX by using a calculated release curve. Import this into Vessfire to evaluate the heat flux effect on pressurized equipment, if rupture occurs go to the second phase.
2) Simulate the rupture in KFX to find new values for net heat flux, and evaluate further escalation in Vessfire.
3) If further escalation occurs document the findings.

Further information around the three phases is presented in section 4.1.

Using the results from part one, suggest improvements/risk reducing measures in the plant and describes their further function. To evaluate the effect of risk reducing measures, one scenario will be chosen as comparison/assessment criteria. Where time to rupture, remaining pressure and amount of gas in the segment will be compared to the comparison/assessment case. This study will further examine effect of blowdown and blowdown procedure at the terminal. And additionally evaluate the effect of risk reducing measures, such as increased wall thickness, insolation etc.

It has previously been conducted similar escalation studies. However, a normal approach to conduct these studies is to use reference values of a uniform property for heat flux both global and peak, and will only record/evaluate if rupture occurs. The values for heat flux used in this thesis are found through simulation and will be presented and used as a function of time. If rupture occurs, further evaluate the rupture or ruptures in a new simulation in KFX. It will in this way be more adapted to the chosen terminal and reality.

This study examines escalation and risk reducing measures to prevent further escalation. The focus is only from a technical point of view and will therefore not consider first and third person risk in the chosen scenarios, or probability for leakage and ignition.

1.4 Work process

Preparation to this task started already during summer of 2012, by learning Kameleon KFX and reading through reports that could be of relevance for the thesis. Date 15.08.2012 the official kick off meeting took place, and access was granted to documentation for the chosen gas process plant (hereby called reference plant). When the assignment was made, Gassco believed there was an all existing 3D geometry of reference plant. However, this was not the case. So to manage the simulations in KFX, the geometry had to be made first in KFXs own geometry model Doozer, with the default value for material property (steel). Doozer is a simple coordinate based model, where the user chose pipe diameter, colour, direction and length. The geometry was drawn after interpretation of some old hand drawn ISO drawings. After a 3 weak delay the simulations could finally start.

In the learning process of KFX there were 2 short briefings/meetings with Computit on how to set up a case and extract results, some mail correspondence and the user manual. After some failing, simulation in KFX was finally running. In the period of 11.11.12 to 16.11.12 the learning process of Vessfire took place in Trondheim. To overcome a long period with simulation I was lucky to get the software and license to Vessfire installed on my personal computer.

Writing the report started early and was an on-going process throughout the semester.

1.5 Assumptions and limitations

Assumptions and limitations used in this study will be described in this section.

Assumptions:

- The study considers normal operation and that all existing measures will function as intended. As described in the risk analysis (2007) [3], with the exception that 1 train will be treated as 1 segment.
- When calculating/simulating the leak flow, the pressure is assumed to be 120 barg for every scenario with exception of scenario 5 starting at 75 barg in Vessfire. For more information about process conditions see chapter 2.
- The process trains in reference plant are assumed to be 0.6 meters above ground level.
- This thesis is a student’s research study based on some degree of interpretation of ISO drawings, the geometry can therefore not be guaranteed to be flawless.
- The simulation tools in this thesis are assumed to be well validated and accepted by the engineering community.

Limitations:

- Vessfire is limited to simulate one segment at a time, and cannot simulate how multiple segments interact on the same vent line.
- Vessfire is limited to simulate one vessel and two blowdown valves.

- Grid adaption in KFX for multiple releases is difficult, and it could in some cases be necessary to lower the upper limit for allowed time step to manage to simulate multiple releases. This will result in increased simulation time. This problem is discussed briefly in chapter 7.
- Grid is typically adapted by the basis of a constant release flow in KFX, for this thesis the leak flow will vary with time, some assumptions must be made, and this is discussed in chapter 7.
- The chosen scenarios are just a few of many possible unwanted scenarios that could occur. Due to this limitation this thesis alone will not give a complete overview of escalation hazards on reference plant.

Under chapter 7 “Discussion”, there will be presented some limitations in the method used in this thesis and what this could mean for the results.

1.6 Geometry used and references

Here is a simple instruction of the build-up and markings in the report. References are marked with numbers, for example [1] “NORSOK standard, Technical safety S-001, edition 4, February 2008” references are found under chapter 9 “References”.

The thesis consists of many figures and graphs, explanations and accompanying text is found below the illustration.

Because reference plant is an actual plant some of the references are kept confidential to not reveal its identity. Confidential references are found in chapter 9, after those that are classified open. The numbers in Figure 2, indicates train numbers (train 1 is the one on the left side).

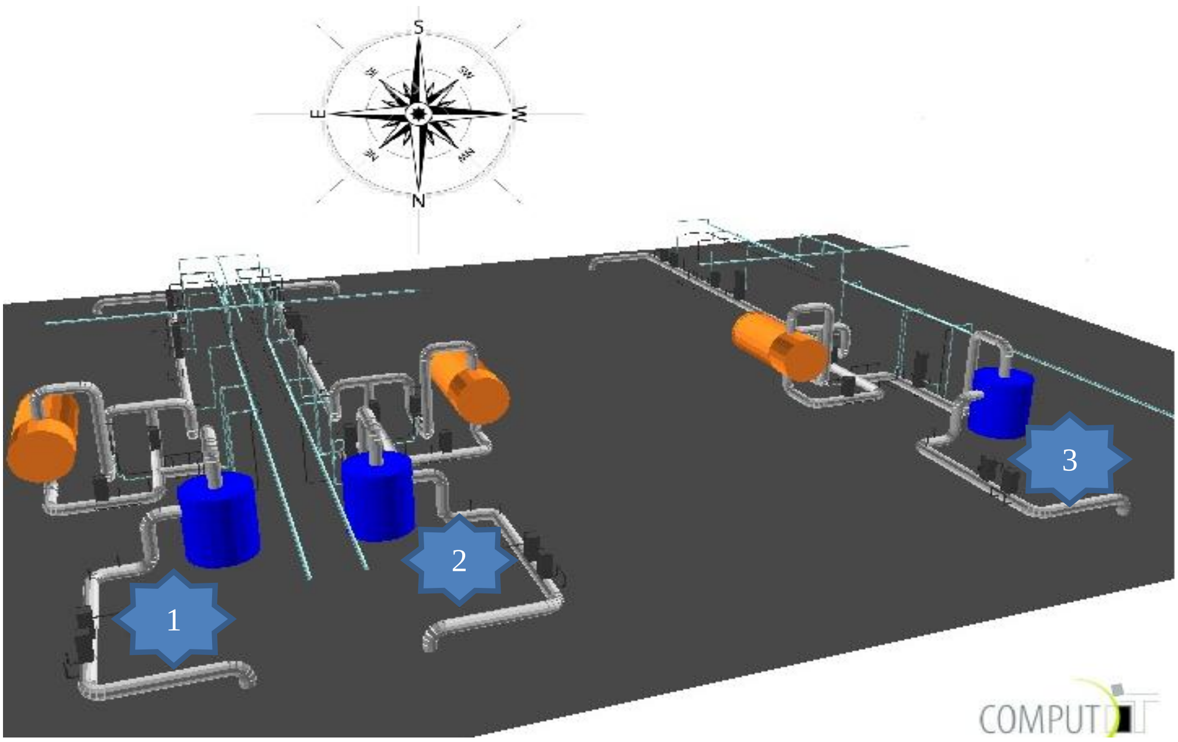


Figure 2 Geometry of reference plant

2 System Description

2.1 Reference plant for consideration.

This thesis will examine the process area for reference plant consisting of three process trains.

The gas terminal is a simple gas process plant consisting of:

- Terminal inlet valve.
- Pig receiver.
- 3 process trains.
- Metering station.
- Terminal outlet valve.
- And some buildings.

Every train consist of an inlet and outlet double block and bleed system with two valves, cyclone separator, heat exchanger, pressure/ control part and two slam shut valves (SSV). The function at the terminal is gas conditioning to downstream marked_as well as filter the inlet gas from the offshore pipeline and meter the outlet gas. When the gas has correct conditions the gas is fed to a downstream metering station located a few hundred meters to the west, for transmission to clients.

As shown in the process flow diagram (figure 3 under), the gas is routed from the offshore pipeline through the pig area, and into the inlet header before going into the trains. After the current operating philosophy all three trains are in production at the same time. Only one train is set out of service to do necessary maintenance. The original design philosophy was to have two trains in operation and one in standby. Every train is nearly identical, and the gas passes first through the cyclone separator from the bottom where solids and liquids are separated from the unprocessed gas, the dry gas exits on the top of the separator. The gas now goes through the first of two SSV.

Downstream of the first SSV, gas enters the heat exchanger with a capacity/effect of 10.7 MW, the gas is here heated up prior to the pressure decrease to guarantee the requirements at the buyers grid. As a result of reduction in pressure is a decrease in temperature, the heat exchanger shall increase temperature to counter Joule Thomsen effect (low temperatures as result from quickly reduction in pressure). The heating medium is a mixture of water and glycol.

After the gas passes the heat exchanger the gas goes through the pressure and control part, as well as the second SSV before being lead through an outlet header and to the metering area. The metering station performs measurement fulfilling after the ISO 5167 and is accordance to the fiscal metering regulations specified by the NPD codes for the quality and quantity of gas to be sent to the downstream plant network.

As shown in the process flow diagram the metering station consist of five metering lines, where after the current operating philosophy all five metering lines is kept in operation, and just as the current philosophy is for the process trains only one metering line is taken out of service for maintenance. There can further be mentioned that each metering line consist of an inlet block valve, an orifice plate and an outlet block valve.

The two SSVs make a High Integrity Pressure Protection System (HIPPS), which has a reaction time less than two seconds. If the pressure in the pipeline exceeds it's given criteria the HIPPS will go from flow control to pressure control. For the second SSV this criterion is 79.2 barg. Should the pressure exceed this limit and the flow pressure control valves fails to decrease the pressure below a set criterion of 83.2 barg, then the first SSV is programed to close. If this for any reason fails, the second SSV will close if the pressure reaches 84 barg downstream. The purpose of this safety system is to make sure that the gas feed to downstream process plants network never exceed theirs maximum allowable operating pressure limit, which is 88 barg [15].

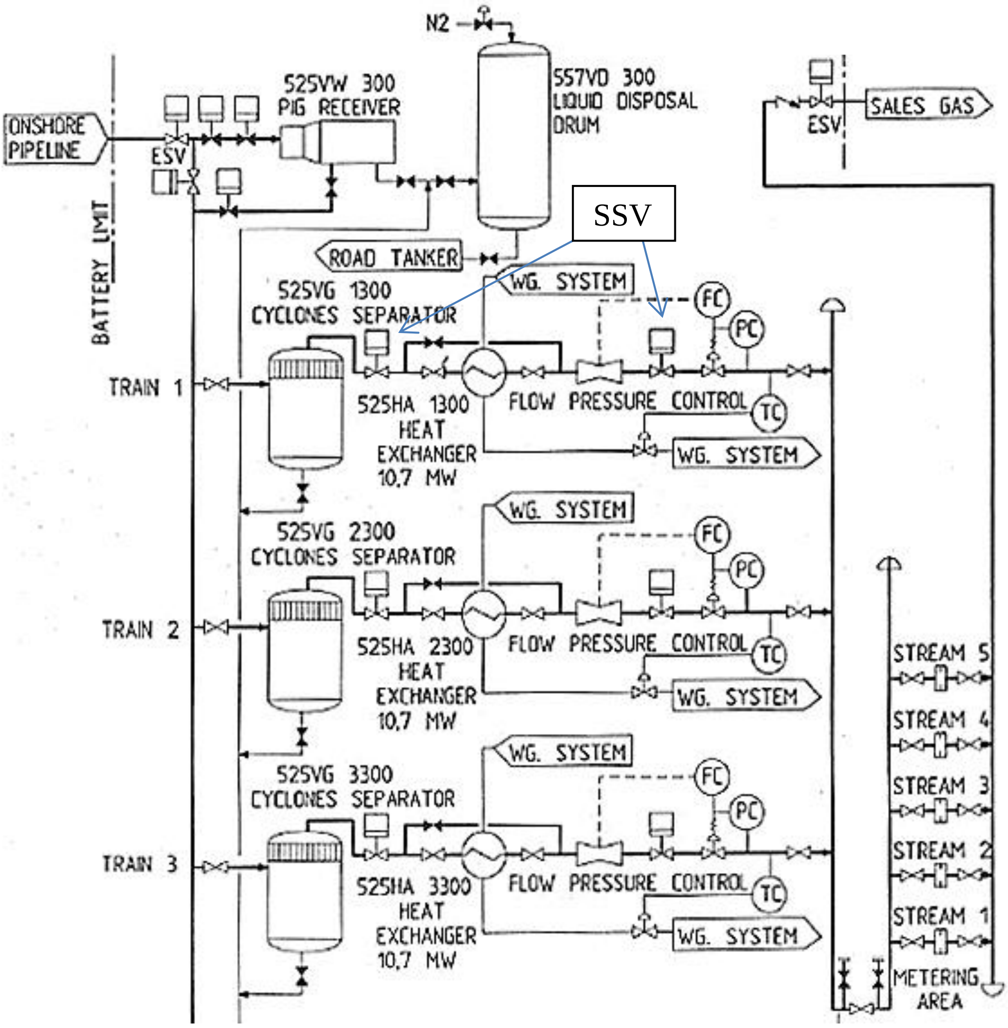


Figure 3 Process flow diagram.

2.2 Venting/ Blowdown system [3, 15]

The plant is equipped with a 10 meters high vent stack, located on the northwest side of the process trains, near the firewater pool. The vent stack has a clearance from other equipment and the property limit (neighbour) of 85 meters. The vent system is a cold vent and is therefore not intended to be ignited, and can be used to depressurize the process plant as well as the onshore pipeline between the landfall valve station (LVS) and the terminal. During normal operation the vent system is flushed with nitrogen. Flushing is interrupted if the network pressure rises above 3 barg. The capacity of the vent is 100 ton/hour. In case of an emergency, the venting system is designed to reduce to half the design pressure or down to 6.9 barg (which is lowest) in 15 minutes for various segments after initiation of blowdown. In case of an emergency all blowdown is manually initiated, remotely from the control rom.

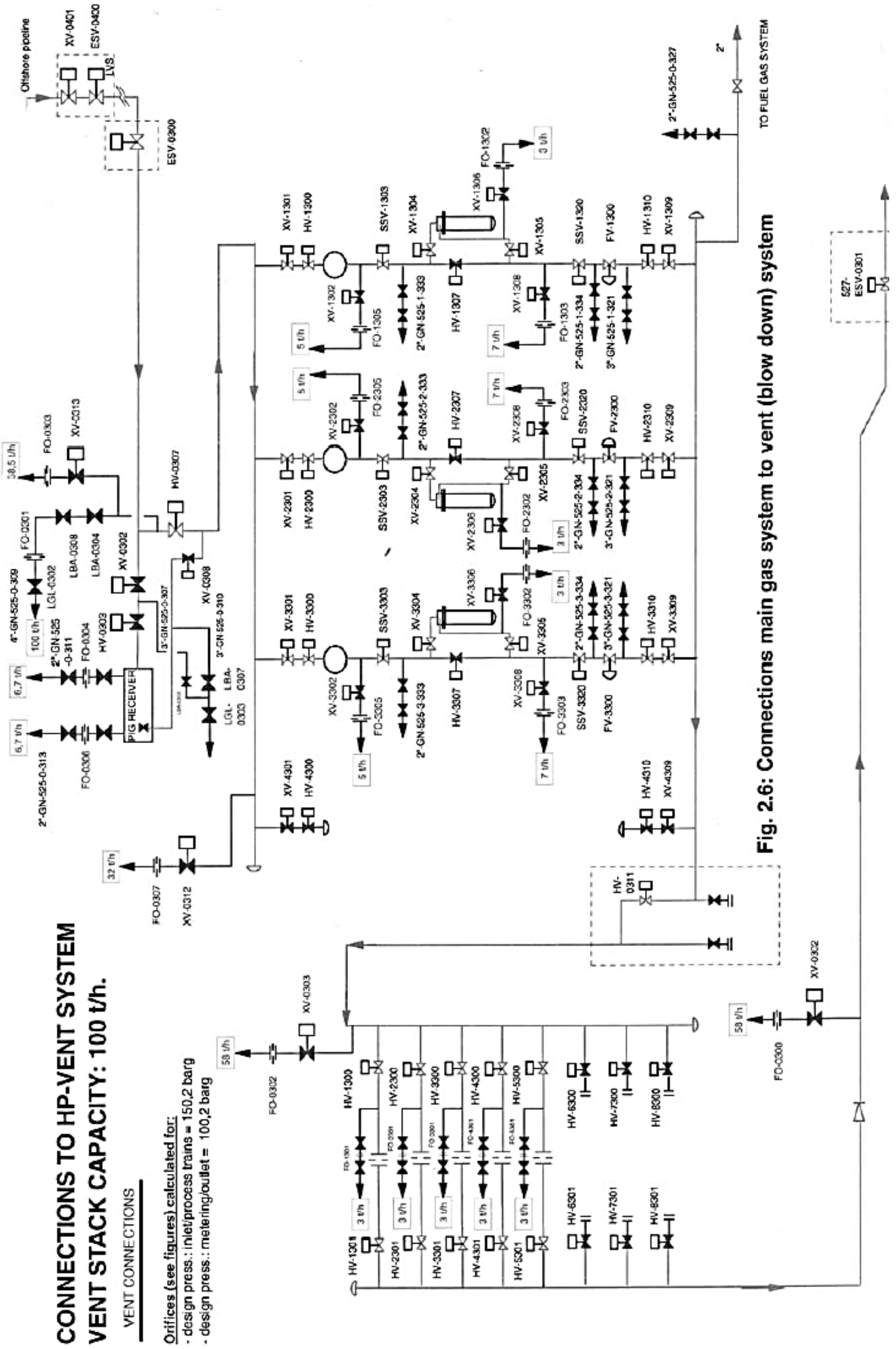


Figure 4 Overview of blowdown system

Figure 4 is an outdated overview over the blowdown system, the changes is an increase in orifice area allowing a higher rate. The rest of the blowdown system is as built.

One train is connected to three BDV lines connected to a blowdown header leading to the vent stack. One train actually consist of three segments. However, due to limitations in Vessfire one train is simulated as one segment.

2.3 Shutdown/ Blowdown procedure [4, 15]

Procedure the process operator is trained after is as followed.

1. When fire is detected the first action is to close the inlet valve. The outlet valve is still open, this means that the downstream plant is still receiving gas. This measure will result in a reduction in the high pressure section of the terminal to about 78 barg.
2. When the pressure reaches 78 barg the outlet valve is closed, and the terminal is sectionalized.
3. The blowdown valves for the exposed segments are opened manually (open manually means in this context that the operator has to start the depressurization, for example "push" the button from the control room), and the upper limit/ restriction capacity for the vent is 100 ton/hour [11]. The restriction value is set due to radiation to nearby equipment and persons should the vent ignite.
    - All 3 trains will be manually depressurized at the same time.

Blowdown is performed sequentially, the sequence is chosen based on the operators judgment, should the fire scenario take place in the process area, all trains are assumed to initiate blowdown in the same sequence.

2.4 Process conditions [3, 15]

The normal design flow at the terminal is a rate on approximately 42 MNm^3/day of dry lean gas. The 3 trains are dimensioned for a flow rate of 21 MNm^3/day.

Table 1 Gas Properties and composition [15].

Component	Mole %
Methane	89.6087
Ethane	5.7725
Propane	1.5353
Iso – Butane	0.2219
N – Butane	0.2427
Iso – Pentane	0.0682
N – Pentane	0.0526
Hexane (C6)	0.0592
Heptane C7	0.0271
Octane C8	0.0061
Nonane C9	0.001
Carbone Dioxide	1.5538
Nitrogen	0.8504
Properties	
Molecular weight [kg/kmole]	18.15
Normal density [kg/Nm3]	0.79

This composition is called dry gas. The trains are designed to separate entrained liquids from the gas, and condition the gas to meet export requirements.

The terminal consists of 2 sections, a high-pressure and a low pressure sections. The operation conditions are listed below.

Conditions upstream let-down [3]:

- Normal operating pressure: 85-146.7 barg
- Max operating temperature: 4.3 ˚C
- Min operating temperature: -4.5 ˚C

Conditions downstream let-down [3]:

- Normal operating pressure: 55-80 barg
- Max operating temperature: 32 ˚C
- Min operating temperature: 2 ˚C

2.5 Process design basis [3]

The design life for exchangeable equipment is 20 years and for the rest of the plant 50 years.

Table 2 Design criteria.

Parameter	Onshore pipeline	Terminal (trains)	
		Upstream HIPPS	Downstream HIPPS
Design pressure (barg)	156.8	150.2	100.2
Max. Design temperature (˚C)	38	50	50
Min. Design temperature (˚C)	-29	-29	-46

There is also an ESV on the inlet and some PSVs on the process area to protect piping if the pressure exceeds the design criteria.

2.5.1 Environmental conditions [3]

The climate at the terminal is referred to as “moderate oceanic”, which gives constant temperate climate year round, for the terminal this is a mean minimum temperature of -8.6°C and a mean maximum temperature of 31.1°C.

The dominate wind direction is southwest with a wind speed between 9 - 5 m/s for about 70 % of the time, a southwest wind with strength 7 m/s is selected to be the default value for wind direction and strength in the chosen scenarios. The chosen wind properties will in some degree affect the result. However, due to the geometry and directions of the simulated jet fires the jet would have exposed pipes anyway (because of short distance between pipes). It should be mentioned that the jets velocity will be of much higher value, and it will therefore control the direction (especially in the start of the jets length, where the momentum is highest).

Figure 5 gives the direction of wind as a fraction of time:

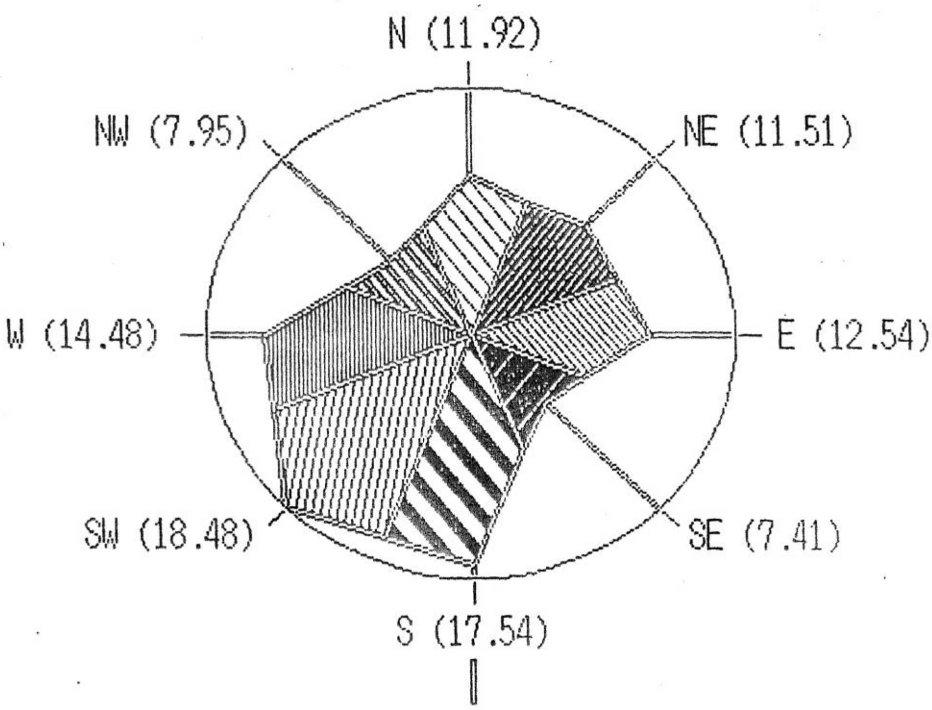


Figure 5 Annual wind direction distribution [12].

3 Basic Fluid Dynamics and simulation theory

This chapter will present the two simualtion tools Kameleon Kfx and Vessfire as well as some relevant theory.

A fire can be defined as a chemical reaction. The process consists of several reactions in which oxygen reacts with a flammable material. In the combustion zone there must be present a proper mixture of fuel, oxygen and energy. Combustion takes place as an exothermic reaction, which means that its releases more energy than is required to initiate the chemical reaction. This short description is only a small part of the thermodynamics that takes place in a fire. All this as well as turbulence is simulated in CFD simulation tools as Kameleon, through different models as the eddy dissipation concept by using different forms of transport equations.

3.1 Transient release and jet fire

The modelling of outflow of gas through holes, aims at predicting the mass flow rate as a function of pressure drop over the hole [13].

A transient gradient means that mass flow varies with time. In this case there will be a direct connection between leak flow and pressure in the segment [13]. If the pressure decreases the leak flow will decrease, in some cases almost linearly (for segments with a large volume and high pressure). When an unwanted scenario occurs and results in rupture of a pressurized part in a system, the pressure in the segment could decrease due to the leak itself and an initiated blowdown.

Mass flow is depended on pressure and temperature in the segment. When pressure decreases or temperature increases the leak rate will decrease. In mass flow calculation conducted both temperature and pressure decreases. The leak rate will still decrease because of the pressure decreases more rapidly, and have a larger effect on the mass flow [13].

A jet fire is a turbulent diffusion flame. Resulting from a continuously release of fuel with significant momentum in a direction or directions. Jet fires can rise from gaseous as well as flashing liquid and liquid inventories [19].

The properties and behaviour of jet fires depend on fuel composition, release conditions, release rate, release geometry, direction and ambient wind conditions. Low velocity two-phase releases of condensate material can produce lazy, wind affected buoyant, sooty and highly radiative flames. Sonic releases of natural gas can produce relatively high velocity fires that are much less buoyant, less sooty and hence less radiative [19].

3.2 Heat transfer [14]

There are 3 forms of heat transfer (convection, radiation and conduction), all 3 will be shortly described.

3.2.1 Convection

Heat transfer by convection occurs when a flame or hot combustion products transport a high amount of energy and comes in contact with other objects. In this study some of the jets are directed into pipelines and other obstacles, this could increase the amount of heat transfer by convection to around 30 to 40 %. [1]. Heat transfer by convection can be explained as transport gradient * heat transfer number, or by equation [27].

$$q'' = h * \Delta T \qquad (1)$$

Where

q''	= Heat transfer by convection per area	[W/m^2]
h	= Convective heat transfer coefficient	[W/m^{2}K]
ΔT	= Change in temperature Kelvin	[K]

The convective heat transfer coefficient is for a total heat transfer of 350 kW/m^2 (assumed 1553 K in change in temperature), when 30 % is due to convection:

$$0.3 * 350000 \frac{W}{m^2} = h * 1553\ K$$

$$h = \frac{0.3*350000}{1553} = 67.6\ \mathrm{W/m^2K}$$

For comparison a convective heat transfer coefficient for air is in the range of 10 to 200 W/m^{2}K [26].

3.2.2 Radiation

Heat transfer by radiation will give the largest contribution of heat in this study, probably in the range of a total of 70 to 80 %. Equation [27];

$$q = \sigma\, T^4\, A \qquad (2)$$

Where

q	= Heat transfer by radiation per unit time	[W]
σ	= $5.6703\ 10^{-8}$- The Stefan-Boltzmann Constant	[W/m^{2}K^4]
T	= Absolute temperature Kelvin	[K]
A	= Area of the emitting body	[m^2]

By literature radiation is known to be proportional to T^4 (see equation 2 above) [14]. Heat transfer by radiation can be a product of a hot flame as well as hot combustion products. The difference between radiation and convection is that convection needs direct contact to an object to transfer heat.

3.2.3 Conduction

Heat transfer in form of conduction occurs when a pipe, some type of metal or something similar lead a large amount of energy from the heat source to a colder environment. Fire escalation in form of conduction requires direct contact between the hot source and the flammable material. The scenarios run in this study will be mainly affected by radiation and convection. Equation for conduction is found in [27].

$$q'' = -k \frac{\Delta T}{\Delta x} \qquad (3)$$

[1] This factor is obtained from discussion with experts in the field of fire simulation, and there is not found any source in literature.

Where

$q^{"}$	= Heat transfer by conduction per area in one direction	[W/m^2]
k	= Thermal conductivity	[W/mK]
ΔT	= Change in temperature Kelvin	[K]
Δx	= Distance	[m]

3.3 General transport equation

Transport equations are partial differential equations describing transportation of one or more physical quantities for example mass, momentum or energy in time and space. A general form for transport equation is [18]:

$$\frac{\partial}{\partial t}(\rho \emptyset) + div(\rho \emptyset u) = div(\Gamma grad \emptyset) + S_{\emptyset} \qquad (4)$$

The first term on the left side in the equation is the transient (time dependent) term, which incorporates transportation of quantity Ø with time (this term will be zero if steady state). The second term represents convective transportation of Ø in relation to a common velocity. The first term on the right hand side describes diffusive (spread, movement) transportation of Ø. And the last term is the source or sink term, describing loss or gain of Ø.

3.4 Eddy Dissipation concept

Eddy dissipation concept (EDC) is a model for chemical reactions in turbulent flow. The model is developed by Bjørn F. Magnussen and his colleges at NTH/SINTEF [6].

In simulations of turbulent flow, the equations are solved for mean values. These values are related to the large turbulence scales. The basis of EDC is physical consideration of the turbulent flow. Combustion occurs where the reactants (fuel and oxidant) are mixed molecular this is manly in the smallest scales. This is also the place where most of the dissipation of turbulence energy into heat occurs. For the reactants to react, the temperature must be high enough and the “residence” time long enough. Hot reaction products must come close and ignite the reaction, and the mix of reactants and products must happen over a long enough duration of time and right mixture for the reaction to occur [6].

EDC have the following main parts [6]:

- Model for energy transmission from large to smaller scales (cascade model)
- By the energy transfer model, characteristic sizes for smaller scale level can be expressed as functions of scales on large scale level. The model gives a connection between large and small scales.
- The large scale level can be connected to mean values in a turbulent model, for example k - Ɛ, or be solved directly through large eddy simulation.
- The model looks on the fine structure as a stationary homogenous reactor. And it is here the chemical reactions happen.
- By modelling the residence time and compare it to the reaction time, makes it possible to model extinguishing.

For fast reactions the reaction-rate is limited to the mixing-rate, which is controlled by turbulence. For reactions with a given reaction time must the residence time in the reactor be larger than the reaction time. Or the result will be local extinguishing.

3.5 k - Ɛ - Model

Averaging the transport equations, results in more unknowns than equations. To make closure of this problem and manage to estimate the effect of turbulence, more equations need to be implemented. A well-known model to solve this problem is the k - Ɛ model.

A turbulent flow can be compared to chaos, with its nature of irregularities and rapid fluctuations in velocity. This nature makes the flow highly diffusive resulting in a significant increase of momentum, mass and energy. The basic physics of turbulent flow is the same as for laminar flow, and the motion for them can be described by Navier – Stokes equations. However the task of resolving the complex physics in a turbulent flow would require extremely fine grid and high time resolution. Even for modern computers this would be a time consuming and intensive task. To overcome this obstacle, the k - Ɛ model can be used. It is well validated and has proven to give good result for a wide range of turbulent flows. In the k - Ɛ model, two transport equations are solved. The first for turbulent kinetic energy, k, and the second for dissipation of turbulent kinetic energy, Ɛ. The effect of turbulence on a fluid flow is taken into account by introducing a turbulent viscosity as a function of k and Ɛ [5, 8].

3.6 Finite volume method

To represent and evaluate the transport equations as a set of algebraic equations, KFX uses a method called Finite Volume Method (FVM). FVM is commonly used in CFD models because of its relation between physical conservation laws and numerical implementation [17]. FVM can shortly be summarized in 3 steps: (1) volume integration of the governing fluid flow equations; (2) discretization of the resulting integral equations into system of algebraic equations; and (3) solving of the discretized by an iterative method.

3.7 Courant number, implicit/explicit and explosive range:

In this section relevant factor, expressions and definitions are presented.

Courant number:
In a flow with a velocity U in x-direction and a grid network with a mesh δx. A particle or a disturbance will use the time $\delta x/U$ on passing the length δx. To solve this in an numerical model the time step δt must be less than $\delta x/U$ [6] that is called the courant criteria.

Courant number for a 1 dimensional case is found from the equation:

$$C = \frac{U\delta t}{\delta x} \leq C_{max} \qquad (5)$$

The value of C_{max} can differ with the solver method used. If an explicit model (time-marching) is used the C_{max} must typical be under 1 to minimize irregularities/ instability. Implicit models (matrix) as KFX are usually less sensitive to numerical instability and can therefore tolerate larger values for C_{max}.

Implicit and explicit:
Implicit and explicit methods are often used as a tool in numerical analysis for obtaining numerical solutions of time-dependent ordinary, and partial differential equations, as is required in CFD modelling.

An implicit method solves an equation involving both the current state of the system and the later state to find the solution. While explicit methods calculate the later state of a system from the current time.

KFX is an implicit code. Which means that the courant number might be larger than 1 and KFX can allow larger time steps [8], without causing instability.

Explosive/flammable range (LEL AND UEL):
A process tank is stored with a given gas composition, a stoichiometric mixture of methane/air. If the fuel air ratio is decreased or increased then the composition will reach the mixture where it's no longer able to propagate a flame. For methane this boundary is 5 (lower) to 15 (upper) volume %. This boundary is called the explosive range, and it is only inside this boundary the gas can ignite. Stoichiometric mixture can be explained as the mixture of chemical reactants which mixture ratio is consistent with the specific chemical reaction equation, example given under.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (6)$$

Explosions are often most intense at/or right over (rich mixture) the stoichiometric mixture [21].

3.8 Introduction to Kameleon

Kameleon KFX is a field model fire simulator, developed by NTNU/SINTEF. KFX is suitable against all safety related issues related to gas dispersion and it can handle jet fires and liquid pool fires. In addition fire suppression using monitors, deluge, sprinkler, and water mist systems can be included in fire simulations and interact with the flow and energy field in the gas phase. KFX includes CAD import capabilities, and is widely used internationally for safety analysis in the oil and gas industry [5]. This section presents some of the models used in KFX, a short description is found under section 3.3.

KFX uses a Cartesian finite volume technique to solve the averaged basic transport equation for each control volume. Equations for the following Favre averaged physical quantities are solved [5]:

- The 3 Cartesian velocity components
- Enthalpy
- Species mass fraction
- Soot mass fraction

Additionally KFX contains many sub models such as the Eddy Dissipation Concept of turbulent combustion, the Discrete Transfer Model for Radiation, Turbulence (k - Ɛ - model), and for the transient development uses KFX a backward Euler Sheet (Unsteady flow are parabolic in time, and therefore it is used "time-stepping" methods like Euler scheme to advance transient solutions step-by-step to compute stationary solutions).

KFX uses a staggered grid system, meaning that the control volumes are staggered relative to each other. This is to obtain a consistent connection between pressure gradient and velocity. This implies that velocity vectors are located at the control volume boundary and the nodes representing the scalar variables, are located midway between this boundary.

When the discrete equations are established in the grid system, it is time to solve them. KFX uses the SIMPLEC algorithm [5] (Semi Implicit Method for Pressure Linked Equations Consistent). The order of calculation is as followed:

1. Use the previous initial pressure and velocity field (for a control volume) from the previous time step.
2. Solve the momentum equations.

3. Solve the equation for pressure correction.
4. Correct the preliminary values for pressure, density and velocity using the pressure correction.
5. Check if the continuity equation is solved satisfied for each control volume (convergence fulfilled). If not repeat from point 3.
6. Solve the equations for other scalar variables (energy equation, turbulence etc.).
7. Execute the necessary corrections between each time step (update the density on the basis of the temperature etc.).
8. Proceed to point 2 to commence a new time step.

The difference between SIMPLEC and SIMPLE (Semi Implicit Method for Pressure Linked Equations) is that SIMPLE neglects some terms in point 3 (pressure correction). The choice of algorithm may affect numerical stability and convergence rate. However, if the solution procedure converges, SIMPLE and SIMPLEC will produce approximately the same results.

3.9 Introduction to Vessfire

Vessfire has been developed by Geir Berge since 1998 as a result of a question posed of the validity of the API RP 521 standard. Vessfire started as a system for calculate the need for passive fire protection. Since then the system has been extensively tested and verified against experiments.

Vessfire is a simulation system for calculation of the effect/ integrity of process equipment exposed or unexposed to fire during a blowdown. The model treats a segment consisting of a vessel, pipes or other equipment containing gas or liquid. A simulation can take one segment and one vessel and as many pipes as the user wants to include into the simulation. The system solves heat transfer in three dimensions for the objects shell, by an amount of grid cells, a wall shell contains of a minimum of two cells. The system also connects the heat transfer thermodynamic processes inside the equipment (due to the difference between heat transfer in fluid and gas). The initial composition is known and based on the inlet composition. The composition in liquid and gas is determined by flash calculations depending on temperature and pressure. This makes it also possible to register phase transition during a running simulation. The inventory processes considered are evaporation, condensing and evacuation through blowdown valves and/or pressure safety valves.

The main characteristic of a jet fire is high heat load over a limited area. This is simulated in Vessfire by using a peak load and a background load. The user can define these loads to expose every part in the simulation. The peak load is intended only to simulate weakening of the object shell, while the background load is intended for heating of inventory (pressure profiles). Vessfire exposes around 1 % of the objects/vessels by the peak load. This value is found through simulations and experiments [16].

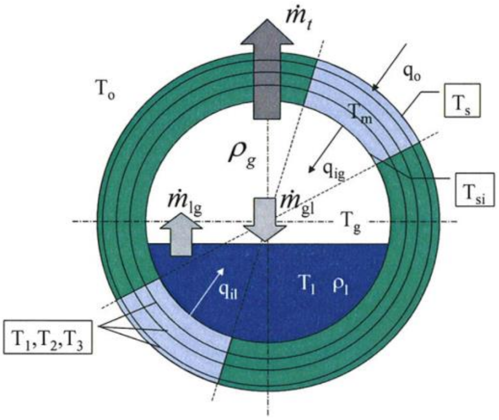


Figure 6 shows some of the parameters governing the process.

Below is listed some of the process that is modelled. The term object includes vessel, and pipes.

- Heat transfer from flame to object shell including convective heat transfer coefficient and emissivity of shell on outside surface.
- Three dimensional heat conduction through material of object shell giving a three dimensional temperature profile (to predict correct temperature distribution in shell and stress due to temperature gradients).
- Modelling of rupture mechanism as function of stress and strain in material.
- Heat transfer from inside surface object shell to oil and gas phase including convective heat transfer coefficient as function of flow (gas phase in vessel).
- Thermodynamic properties of gas and liquid phase as function of composition, temperature and pressure.
- Change in composition of gas and liquid phase as function of time due to change in temperature and pressure.
- Mass transfer between liquid and gas phase due to evaporation of liquid (flashing simulation).
- Mass transfer between gas and gas liquid due to evaporation of gas (flashing simulation).
- Heat transfer between liquid and gas phase.

Information about Vessfire is found through discussion with Geir Berge and in the User manual [16].

4 Leak scenarios

Chapter 4 will present selected leak scenarios, and will form the basis for the thesis. The scenarios are chosen through discussion and reading the risk analysis for reference plant [3]. There will not be given any scenario history prior to the leak, or be mention how the leak is ignited, due to the main focus and priority of this study is fire escalation and effect of blowdown (the area of concern is after the leak is formed). Therefore are scenario 1 – 5 assumed to be instantaneously ignited. Every Scenario will involve the volume contained in the pipeline between valves XV 1301/2301 to XV 1309/2309. The values given in Table 3 are used in every simulation as default values. However, values that apply only to a specific scenario will be presented in its respective section.

Table 3 Scenario information for all scenarios

Description	Values
Ambient temperature	11 ℃
Ambient pressure	1 atm
Gas composition	Se chapter 2
Wind strength	7 m/s
Wind direction	South west
Initial pressure	120 barg
Process temperature	0 ℃
Segment volume	30.6 m^3
Blowdown orifice area	0.00058928 m^2 [2]
Control volume	Approximately 1.2 million [3]

Some scenarios used in KFX will be simulated in Vessfire. To conduct these simulations in Vessfire additional information is needed, this information is given in section 4.10. All pictures and figures presented in this chapter are only for illustration purposes. Simulation result will be presented in the next chapter. In every leak scenario there is imported a mass flow leak file into KFX calculated after equations from TNO Yellow Book [13] (see Graph 1 in section 4.2).

[2] This is the combined value of all three orifices on one segment
[3] Every simulation in KFX has approximately 1.2 million control volumes; this value may vary by a few thousand.

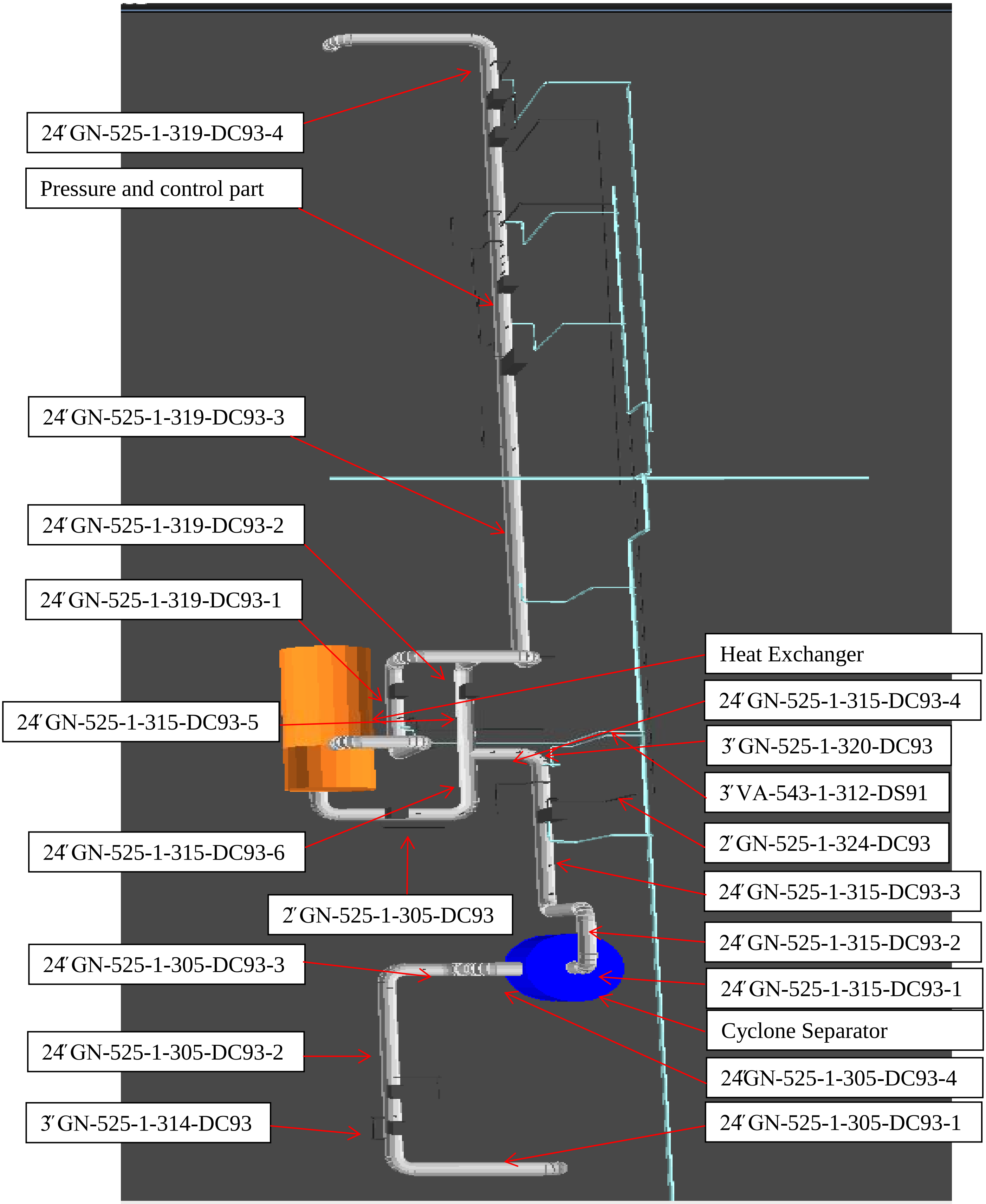


Figure 7 Pipes location and tag numbers on train 1.

Every pipe has a specific identification number called tag number, in this thesis pipelines will be referred to by their tag numbers. On the previous page there is a simple sketch over the first process train. Every pipe mention in this thesis is marked in Figure 7. A simple explanation of factors the reader should know in the tag number is as followed:

24”GN-525-1-319-DC93-1, whereas 24“ (24 inches) is the pipe dimension, the factor 1 meaning train 1, 319 is the pipe identity, DC93 is material class and the last number is a factor that have been added for having smaller pipe parts in Vessfire.

All initial leaks are placed with an altitude of 0.9 meters above ground.

4.1 Logging results and running the simulations.

For logging results in KFX, bullet monitors are used to find the net heat flux to structures and equipment. Bullet monitors enables detailed calculations of net heat flux on solid objects. Bullet monitors stores radiation intensities calculated by ray tracing on a spherical surface. When there is a given intensity distribution over the sphere taken in one point, the radiation heat flux for the chosen object normal can be calculated by vector multiplication. Bullet monitors also stores values for properties by empirical relations to estimate convective heat transfer and reconstruct the geometry to present isocontoures on solid surfaces [8]. There are two ways of placing bullet monitors, number 1; place bullet monitors in a self-described grid pattern or number 2; let KFX place them in a coordinate list constructed by the geometry used. Every simulated scenario in this study is simulated with bullet monitors in a coordinate list. The default value of number of ordinates is 200, this should be sufficient in capturing near field radiations for reference plant (heat loads that can have significant impact on objects). Far field calculations (heat loads from 0-10 kW/m^2) requires a higher number of ordinates to make the results reasonably accurate, in KFX user manual this number is given as one thousand ordinates. The first simulated scenarios had 300-600 ordinates, the escalation scenarios have between 1500-2000 ordinates.

When processing the result in KFX an assumed surface temperature throughout the simulation of 288 K is used. This means that the figures showing net heat flux to structures and equipment (radiation and convection heat absorbed and transmitted by pipes and structure) radiate out about 50 W/m^2 (reflected radiation), since this is such a minor value this will therefore be treated as incoming heat flux/irradiation and convection in Vessfire.

Vessfire calculates the amount of absorbed, reflected and transmitted heat flux.

The simulations will be simulated and evaluated in 3 phases:

1) Find the values for net heat flux on objects in KFX by using a calculated release curve. Import this into Vessfire to evaluate the heat flux effect on pressurized equipment, if rupture occurs go to the second phase.
2) Simulate the rupture in KFX to find new values for net heat flux, and evaluate further escalation in Vessfire.
3) If further escalation occurs document the findings.

4.2 Initial release flow

The initial release rates are calculated after TNO Yellow Book [13], this marks the initial event and start of the thesis. Modelling of outflow of gas through holes aims at predicting the mass flow rate as a function of pressure drop over the hole.

Mass flow rate for gas outflow through an orifice can be calculated by a generalised equation.

$$q_s = C_d * A_h * \Psi * \sqrt{(\rho_0 * P_0 * \gamma(2/(\gamma+1))^{\frac{\gamma+1}{\gamma-1}}} \left(\frac{kg}{s}\right) \qquad (7)$$

With

$$\gamma = C_p/C_v \qquad (8)$$

Where

q_s = Mass flow rate [kg/s]
C_d = Discharge coefficient [-]
A_h = Cross- section area hole [m^2]
Ψ = Outflow coefficient [-]
ρ_0 = Initial gas density [kg/m^3]
P_0 = Initial gas pressure [N/m^2]
γ = Poisson ratio [-]
C_p = Specific heat at constant pressure [J/(kgK)]
C_v = Specific heat at constant volume [J/(kgK)]

Factors like pressure and density will changes as the depressurization process progress. The value for C_d is set to 0.62 [13]. Pressure change is calculated by equation:

$$P = P_0 * \left(\frac{M}{M_0}\right)^{\gamma} \qquad (9)$$

Where

M_0 = Initial mass [kg]
M = Mass [kg]
P = Gas pressure [N/m^2]

As the amount of mass in the segment decreases as will the pressure, to find the next time step (new value for mass flow), new value for pressure is calculated and used in equation 7. A similar calculation is done for the temperature.

Change in density is calculated by equation:

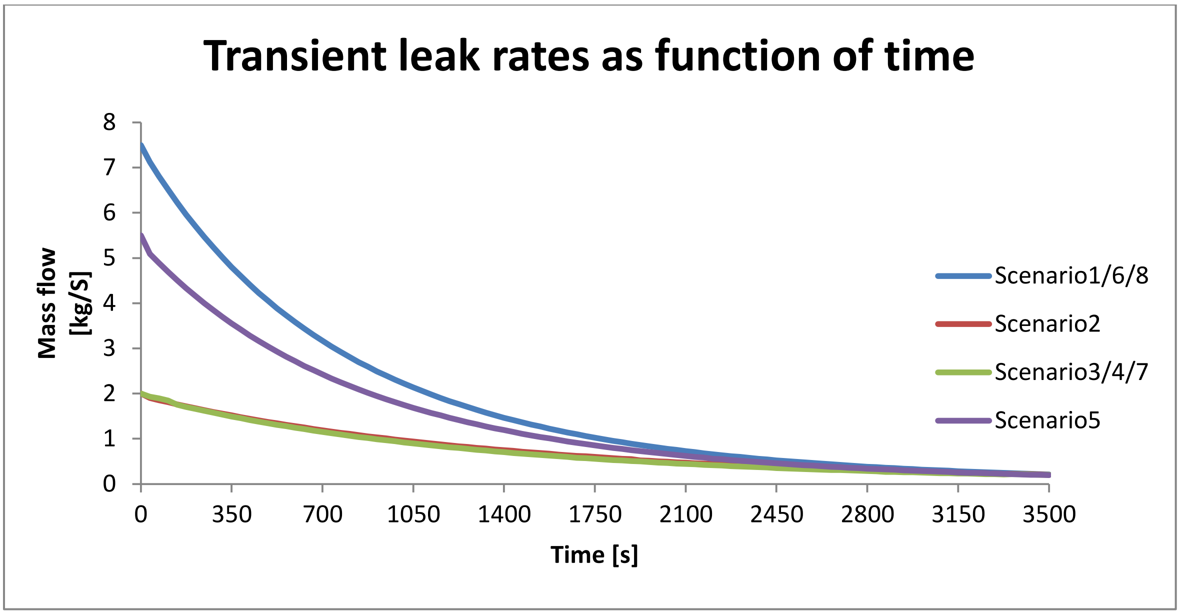
$$\rho = P/(R_{gas} * T) \qquad (10)$$

Where

R_{gas} = Specific gas constant [kg]
T = Temperature [N/m^2]

The mass flow rate will be on its highest value in the beginning when the pressure is highest. A reduction in pressure and density will result in a decrease in mass flow. Curves shown in Graph 1 are used in KFX and the leak flow will behave in this manner throughout the simulation. In these calculations[4] both leak flow and initiated blowdown will depressurize the segment.

[4] The author of the calculation sheet is Jerome Renoult.



Graph 1 Calculated leak flow as function of time

Reference plant's gas and process properties are used in defining these curves. Values used in the calculation sheet are shown in Appendix C.

4.3 Scenario 1, high release flow.

In scenario 1 a hole with diameter of 1 inch (2.54cm) is formed. The leak is ignited instantly, creating a jet fire with a starting release flow of 7.5 kg/s. For initial leak rates see Graph 1 in section 4.2 (above).

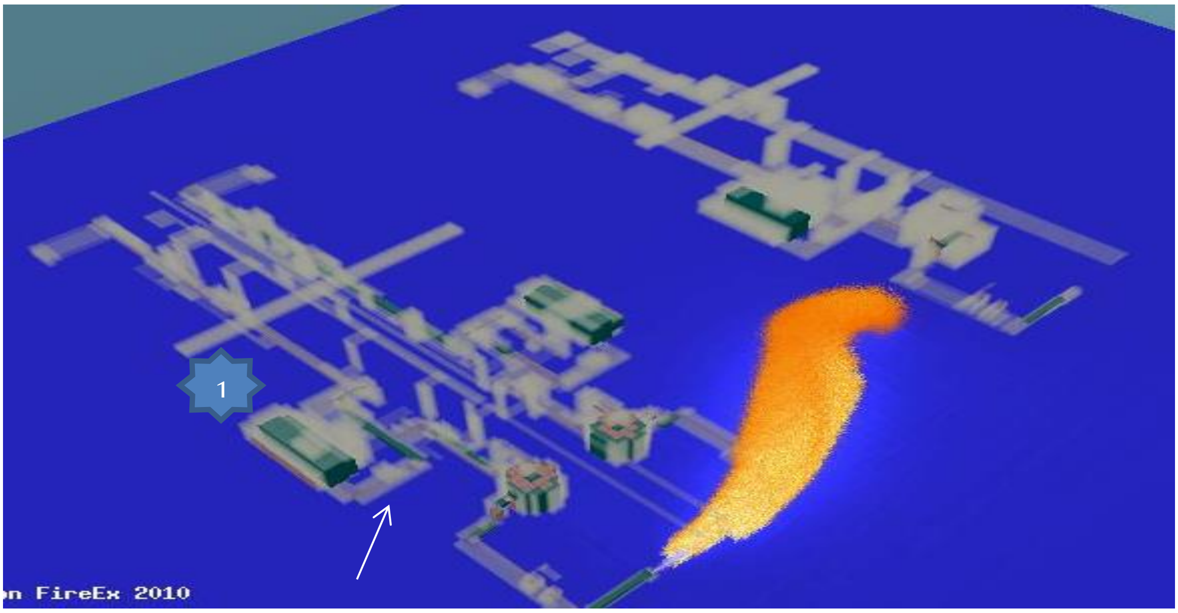


Figure 8 Scenario 1; Jet fire after 60 seconds.

Leak flow in Figure 8 is 6.9 kg/s directed west engulfing parts of train 2, the reach of the jet is approximately 25 meters. The purpose with the scenario is to see how the jet behaves when hitting a 24 inches vertical pipe straight on. The white arrow represents wind direction. Number 1 indicates the location of train 1.

4.4 Scenario 2, directed towards heat exchanger.

In scenario 2 a leak hole with diameter 0.5 inch (1.27cm) is formed, giving a starting leak flow of 2 kg/s. An extract from this scenario simulation report in Vessfire is found in Appendix A.

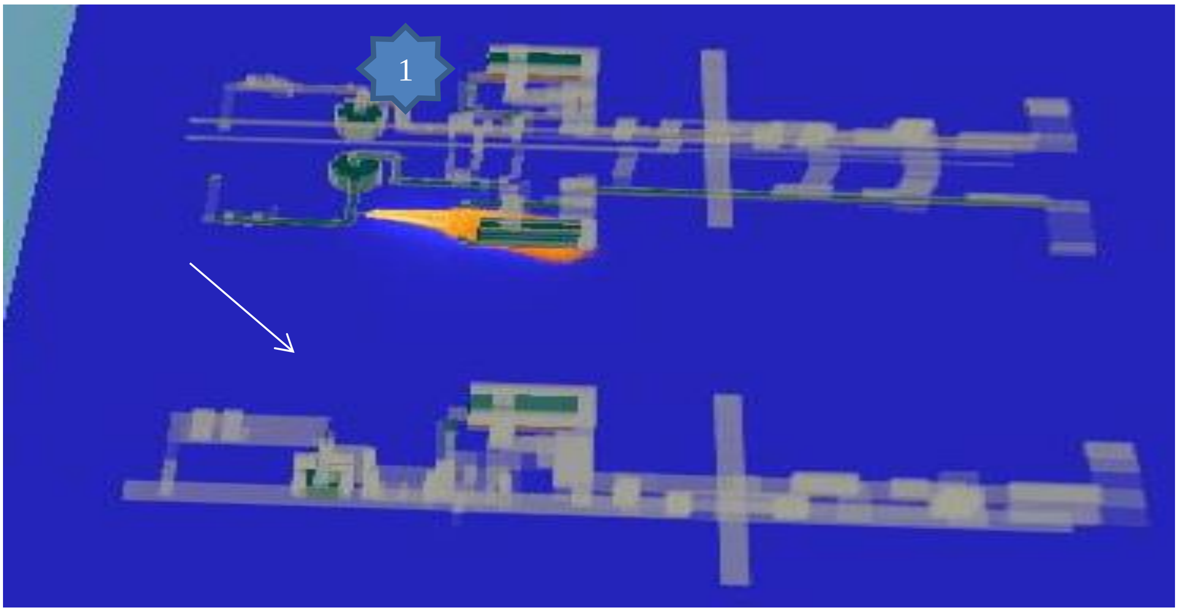


Figure 9 Scenario 2; Jet fire after 60 seconds.

Leak flow in Figure 9 is 1.9 kg/s directed south, engulfing the heat exchanger on train 2. Train 1 is briefly affected. Length of the jet is approximately 15 meters. White arrow represents wind direction.

4.5 Scenario 3, leak from train 1.

A hole with diameter 0.5 inches is formed, and releases a mass flow of 2 kg/s. The leak is ignited instantly, creating a jet fire.

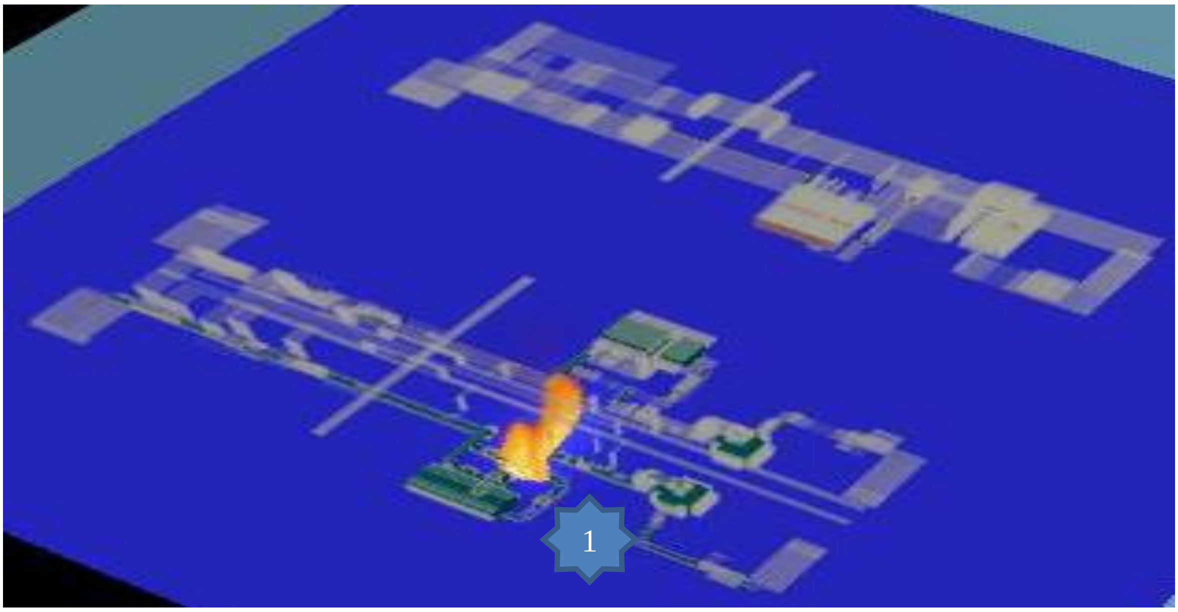


Figure 10 Scenario 3; Jet fire after 90 seconds.

Leak flow in Figure 10 is 1.8 kg/s directed west, embracing pipes on train 1 and 2. Length of the jet is approximately 12 meters.

4.6 Scenario 4, increased distance.

Scenario 3 and 4 will have the same background history. However, the difference is that the leak is now targeting train 3 from train 2. The distance here is larger (the distance between train 1 and 2 is around 7 meters, and between train 2 and 3 around 20 meters). This to see what there is to gain from having a more inherent safety design, which in this case is larger distance between hazardous objects.

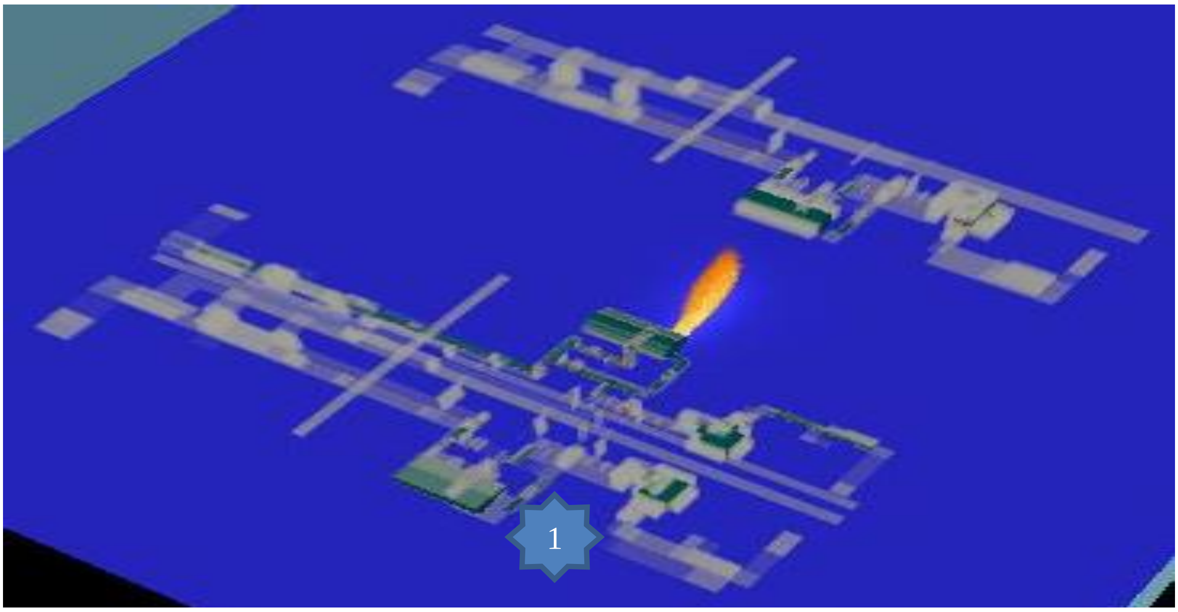


Figure 11 Scenario 4; Jet fire after 150 seconds.

Leak flow in Figure 11 is 1.75 kg/s directed west targeting train 3. Length of the jet is approximately 15 meters.

4.7 Scenario 5, directed into the ground.

A hole with diameter 1 inch is formed, and releases a mass flow of 5.5 kg/s directed into the ground. The leak is ignited instantly, creating a jet fire. This scenario is located in the low pressure part of train 1, pressure and temperature in this part of the segment is set to 78 barg and 16°C, this is the reason why the leak flow is lower than for scenario 1.

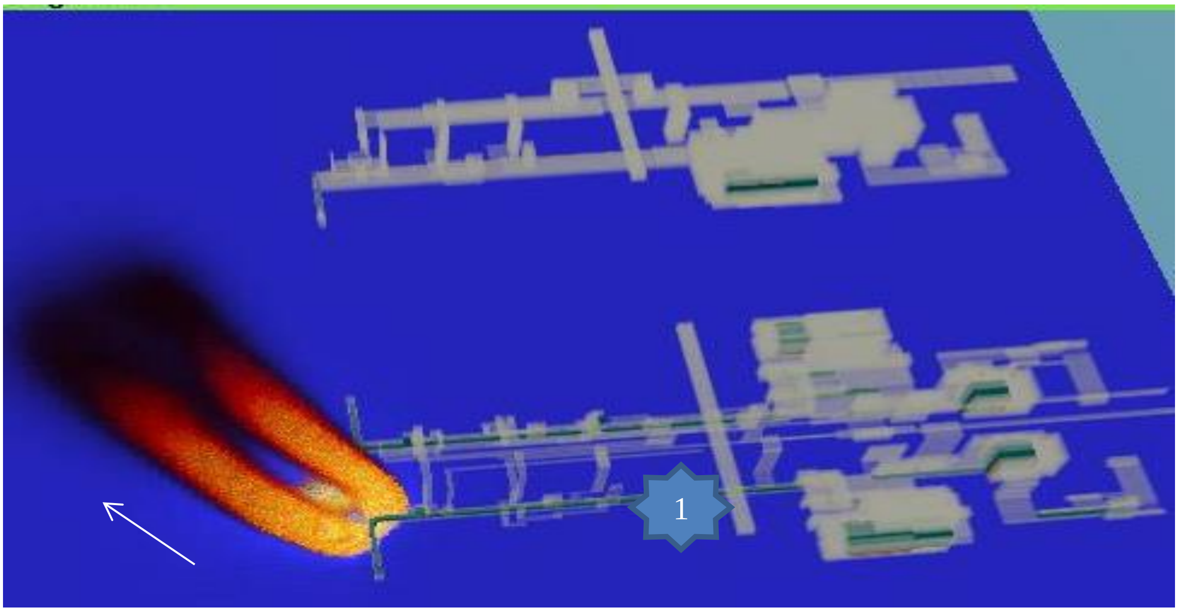


Figure 12 Scenario 5; Jet fire after 140 seconds.

Leak flow in Figure 12 is 4.5 kg/s directed into the ground, KFX records large amount of combustion products (the black area at the end of the jet fire). Train 1 and 2 is briefly affected. Length of the jet is approximately 35 meters. White arrow represents wind direction.

4.8 Scenario 6, ignition delay high release flow.

Same leak origin as scenario 1, with the difference that this scenario has a pre-defined time delay on ignition on 175 sec, this to evaluate gas dispersion and how the ignited gas cloud will contribute to the net heat flux on piping before the jet is stabilized.

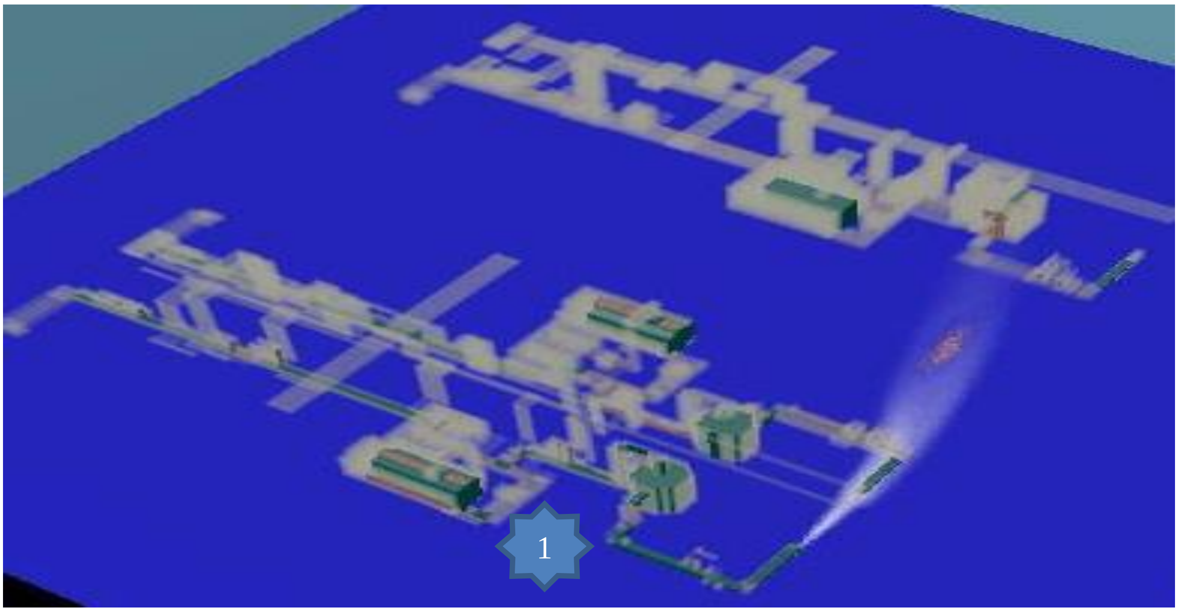


Figure 13 Scenario 6; Gas cloud/jet starts to ignite after 190 seconds.

Leak flow in Figure 13 is 5.8 kg/s directed west, the ignition cell is placed between train 2 and 3. The length of the jet is approximately 30 meters.

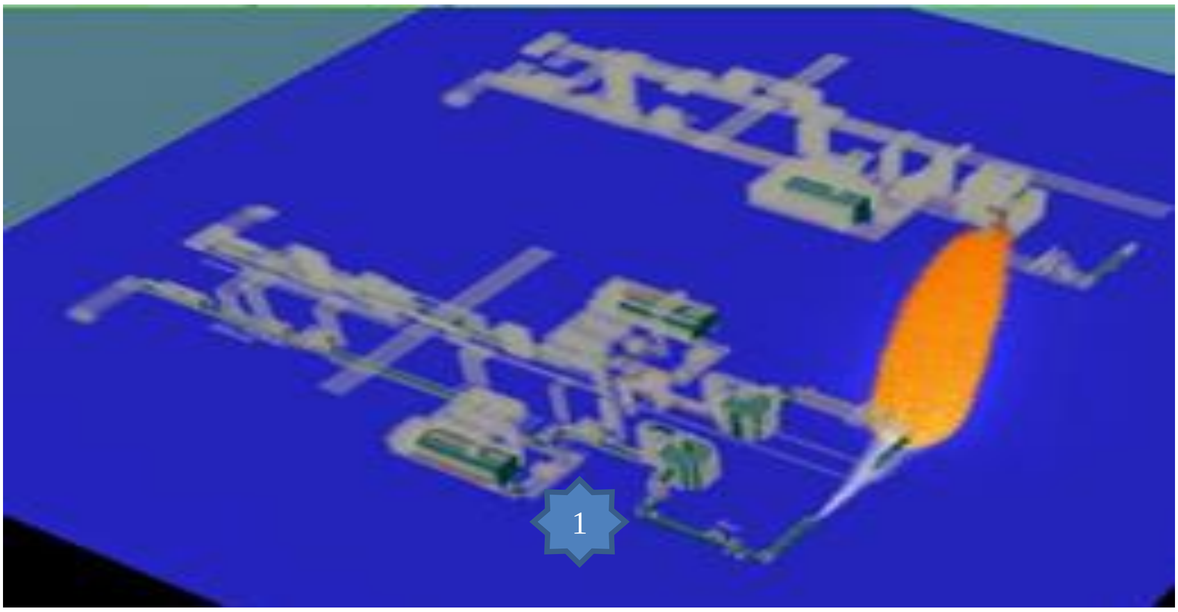


Figure 14 Scenario 6; Developed jet fire after 200 seconds.

Leak flow in Figure 14 is 5.7 kg/s, cold gas is embracing the start of train 2 and the jet fire reaches and affects some parts of train 3. Length of the jet is approximately 30 meters.

4.9 Scenario 7, ignition delay low release flow.

Scenario 7 has the same background history as scenario 3. However, also here there is a pre-defined time delay on ignition similar to scenario 6 (175 sec, leading to a gas cloud to form prior to ignition).

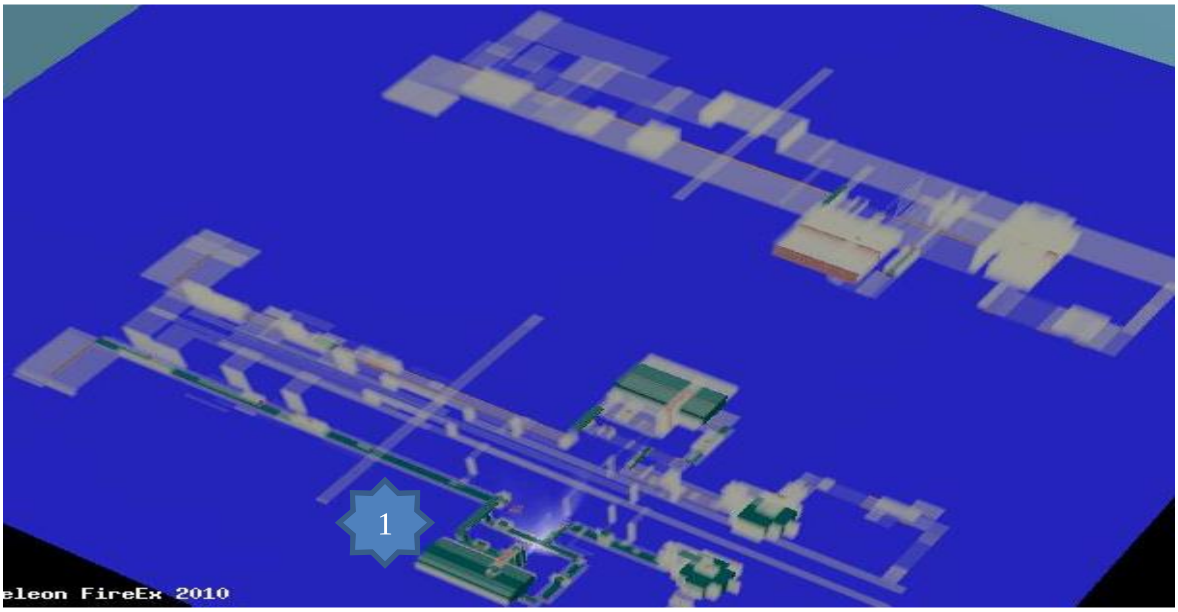


Figure 15 Scenario; Jet 185 seconds.

Leak flow in Figure 15 is 1.7 kg/s directed west. In Figure 15 an orange mark in front of train 1 heat exchanger is indicating that the jet is igniting. Length of the jet is approximately 5 to 10 meters.

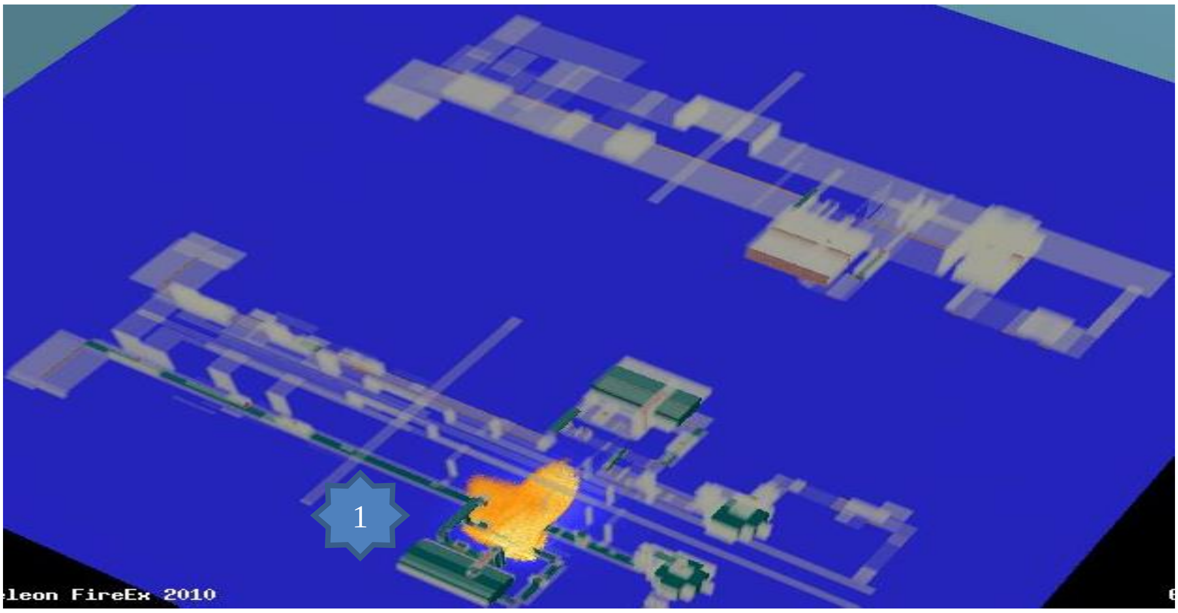


Figure 16 Scenario 7; Fully developed jet fire after 200 seconds.

Leak flow in Figure 16 is 1.7 kg/s, a fully developed jet fire embracing parts of train 1 and affecting in some degree train 2. Length of the jet is approximately 10 meters.

4.10 Scenario 8, gas dispersion.

Scenario 8 has the same input/ background as scenario 1 and 6. However, it will not ignite. This to examine gas dispersion, and to evaluate if a gas cloud will form, if so how will the cloud behave when there is a transient behaviour in the leak.

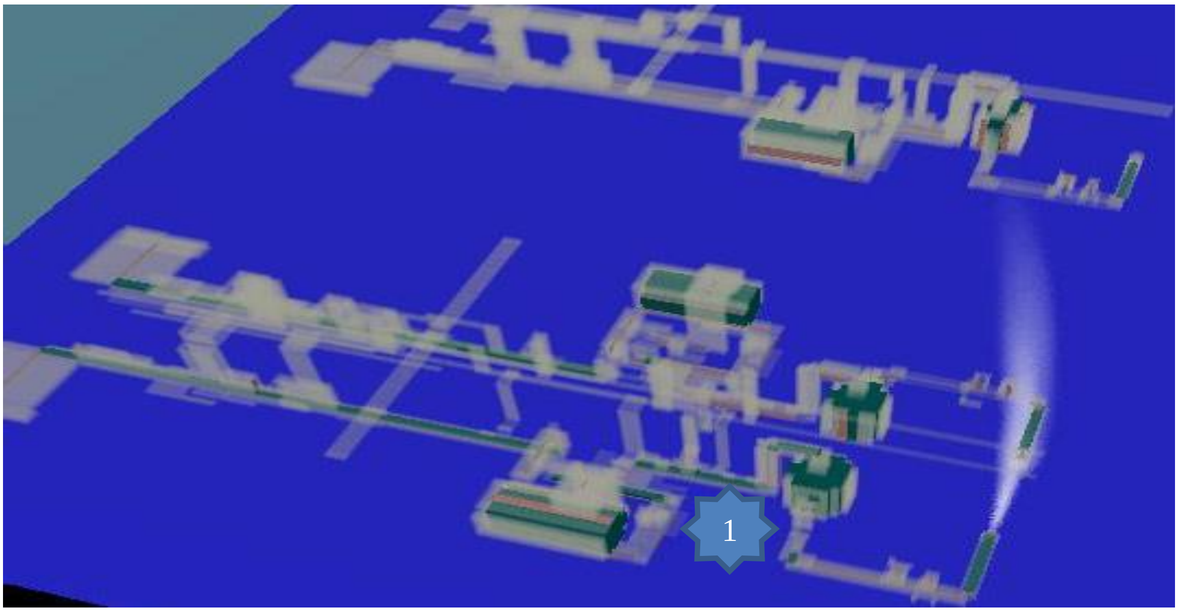


Figure 17 Scenario 8; Gas dispersion after 205 seconds.

Leak flow in Figure 17 is 5.7 kg/s directed west embracing the start of train 2 and reaches train 3, vol% is given in chapter 5.4. Length of the jet is approximately 28 meters.

4.11 Additional Information Vessfire.

Additional information is needed for Vessfire. The additional information and the simulation purposes/scenarios for Vessfire are in this section.

Table 4 Additional information Vessfire.

Object	Shell material	Stress factor	Material strength	Outer diameter	Wall thickness	Increased wall thickness	Insulated
24"GN-525-1/2-305-DC93	CS_360LT	95 %	500 MPa	0.61 m	0.0305		No
24"GN-525-1/2-315-DC93	CS_360LT	95 %	500 MPa	0.61 m	0.0305		No
24"GN-525-1/2-318-DC93	CS_360LT	95 %	500 MPa	0.61 m	0.0305		No
24"GN-525-1/2-319-DC93	CS_360LT	95 %	500 MPa	0.61 m	0.0305		Yes
3"GN-525-1/2-314-DC93	CS_360LT	95 %	500 MPa	0.0889	0.0071	0.0142	No
3"GN-525-1/2-320-DC93	CS_360LT	95 %	500 MPa	0.0889	0.0071	0.0142	No
3"VA-525-1/2-312-DS91	CS_360LT	95 %	500 MPa	0.0889	0.0071	0.0142	No
2"GN-525-1/2-318-DC93	CS_360LT	95 %	500 MPa	0.0603	0.0055	0.011	No
Cyclone Separator	CS_360LT	95 %	625 MPa	1.34	0.055		No
Heat Exchanger	CS_360LT	95 %	625 MPa	1.7 m	0.1		Yes

Only pipelines with a given heat load is described in Table 4. However, the information will be representative for other similar pipelines used in the simulation.

Pipes in this thesis are of a material class corresponding to API 5L-X60, which has a minimum tensile strength of 517 MPa. A conclusion was made in 2006 [4] that a reasonable choice of pre-defined data for reference plant in Vessfire is a material curve for carbon steel (CS 360LT) with a starting value for tensile strength of 500 MPa at 293 degree Kelvin.

Pipe diameters are specified as outer diameter in ASME B36.10 corresponding to the pipe dimension given in the table above. Wall thickness is specified in reference [4] and document number DO24-C-500-L-SG-001, Table III.

Vent system backpressure (pressure in the piping on the vent side) is set to 1 atm.

In all simulated scenarios in Vessfire 1 train will be treated as 1 segment. The various factors in the simulations will be leak flow, insulation, orifice size, wall thickness, activation time for initiation of blowdown and various heat loads for peak and global.

For every simulation in Vessfire, pressure in the segment is set to 120 barg when the simulations start (only blowdown and a possible leak will depressurize the segment), if not otherwise is described (why this value for pressure is set will be discussed in chapter 7).

5 Simulation results

In this chapter results from every simulated phase (phases one - three) simulated both in KFX and Vessfire as well as gas dispersion are presented. Scenario 2 (2 kg/s leak embracing heat exchanger on train 2) third phase will be simulated with 78 barg pressure in the segment, to evaluate how the difference in pressure will affect the blowdown process.

5.1 First phase, the initial event.

This section will present results from every chosen scenario that is evaluated both in KFX and Vessfire.

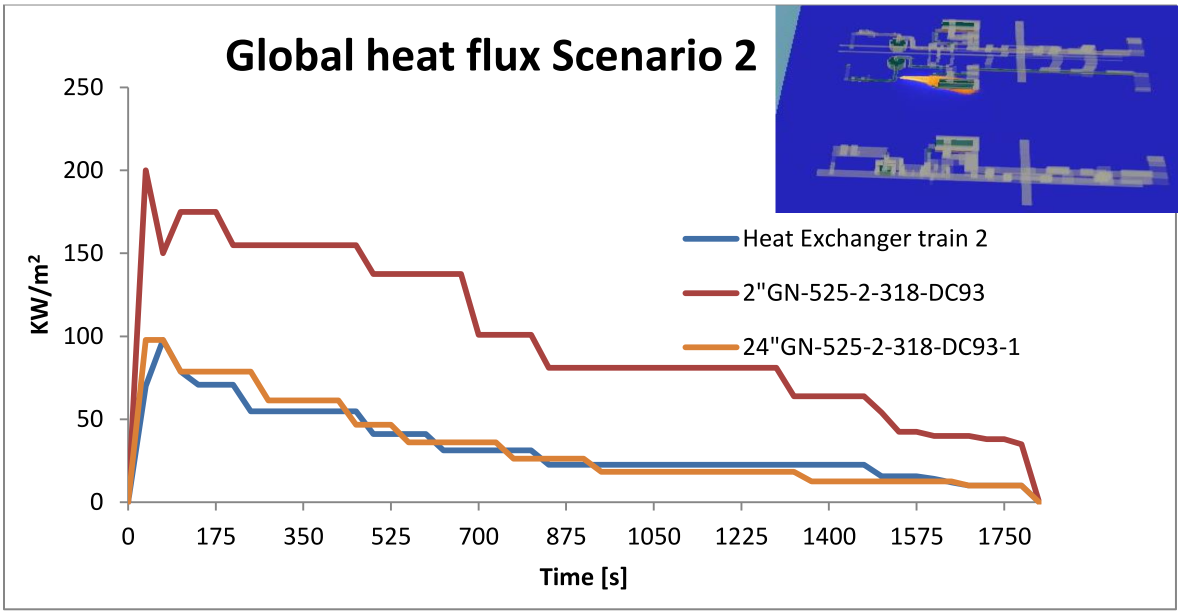
As a result of the input, KFX presents simulation results as figures where heat loads are shown as imprints on objects. From these figures graphs for global and peak heat fluxes are found by visual interpretation. Factors like heat load and affected area are used in defining an averaged based background heat flux, and a maximum peak load affecting a specific pipe and/or segment part. The method used is considered to be conservative due to heat flux is shown by colour, and each colour represents a range (250-300 kW/m^2 is marked with the same colour), the value chosen is always the highest. In all cases global background heat loads and peak loads of flux will be defined as function of time.

Only the most affected pipes will be given a heat load. Scenario 4 will not be mentioned in this phase, due to large distance between train 2 and 3 (lower values for heat flux are recorded on train 3). And scenario 6 is chosen instead of scenario 1 (with a pre-defined time delay, allowing a gas cloud to be formed prior to ignition). For some peak heat loads more than one pipe is given the same value, due to there were negligible differences between the actual values.

5.1.1 Scenario 2, directed towards heat exchanger.

Scenario 2 takes place on train 2 with a starting value for mass flow of 2 kg/s, only pipes and the heat exchanger on train 2 are recorded with a significant value of heat flux.

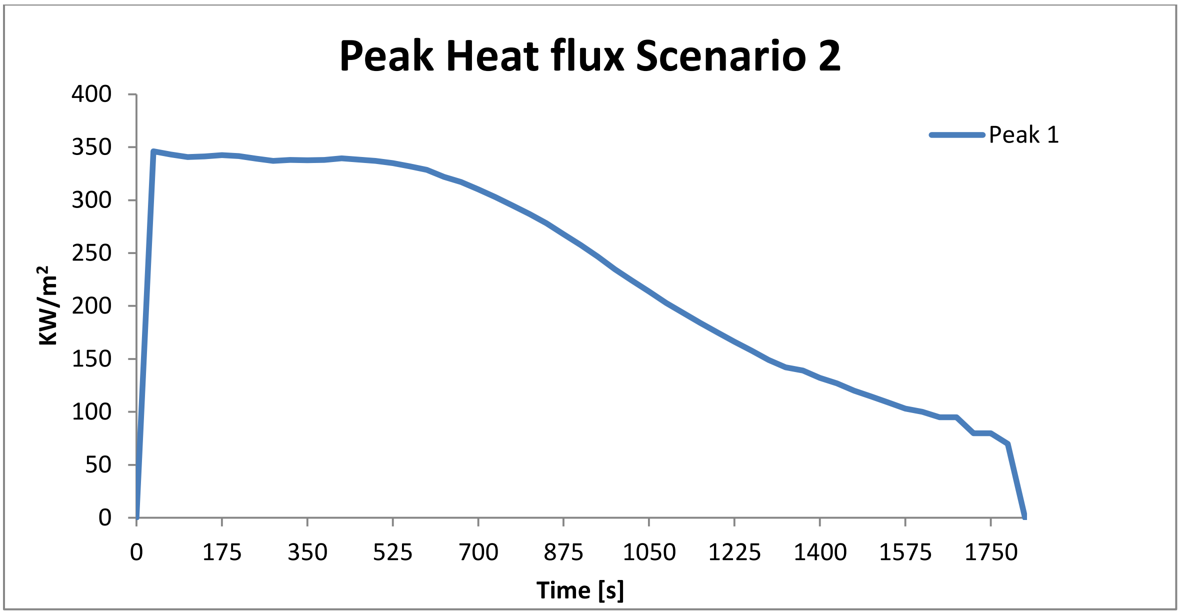
First presented are global heat loads:



Graph 2 Scenario 2; Global heat fluxes.

The global heat fluxes will for all pipes decrease. Every curve will after 700 seconds stabilize for around 600 seconds, before continuing to decrease. The value for the 2" pipe (red curve) will have a highest value of 200 kW/m^2 for a short period of time.

These values as the rest presented in this chapter for global heat flux are found in KFX and used in Vessfire to estimate pressure developments inside process segment (heating of inventory)[16].



Graph 3 Scenario 2; Peak heat fluxes.

As mentioned, some peak heat loads are divided into groups because more than 1 pipe has the same curve. The value of peak 1 is given to the following pipes.

Peak 1: 2"GN-525-2-318-DC93and 24"GN-525-2-318-DC93-1

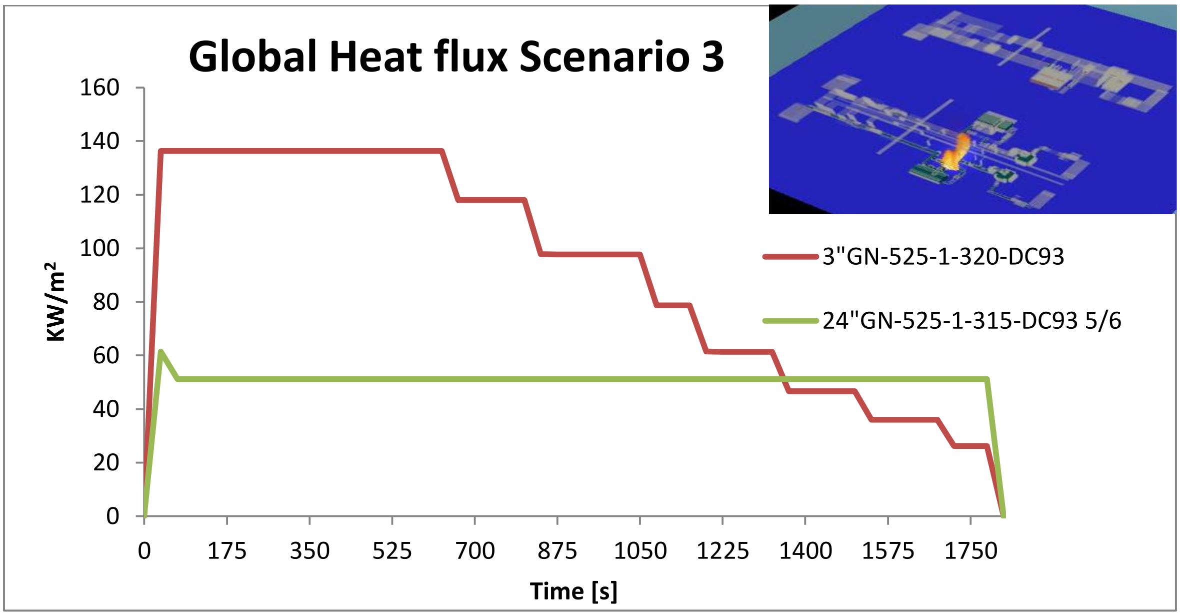
The curve starts at 350 kw/m^2 and is actually almost stabile for around 650 seconds before it decreases and is halved after 20 minutes.

The peak heat fluxes are used in Vessfire to assess rupture [16].

5.1.2 Scenario 3, leak from train 1.

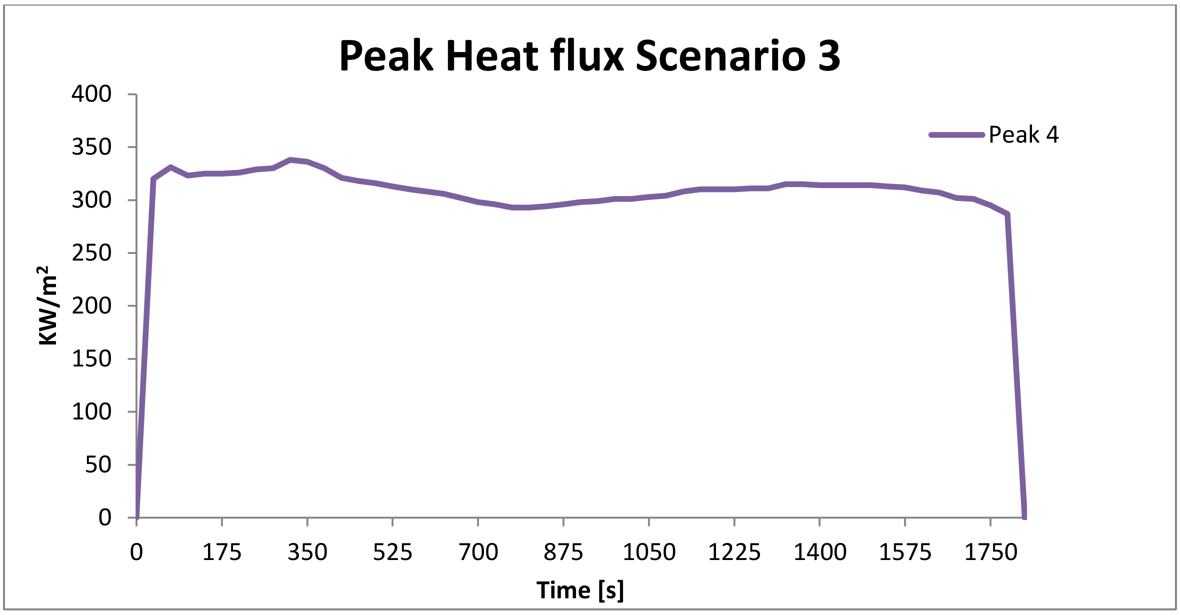
As for scenario 2, in scenario 3 there are only recorded significant values for heat flux on pipes connected to the same train as the initial leak occurs on (initial leak rate 2kg/s on train 1).

Heat flux found in scenario 3, first presented global heat fluxes:



Graph 4 Scenario 3; Global heat fluxes.

For the 3" pipe the global heat flux were almost constant, there were small nuances in variation in the results the first 650 seconds, before it decreases. The value for the 24" pipe is constant, due to its position to the jet fire (the jet is directed into the pipe).

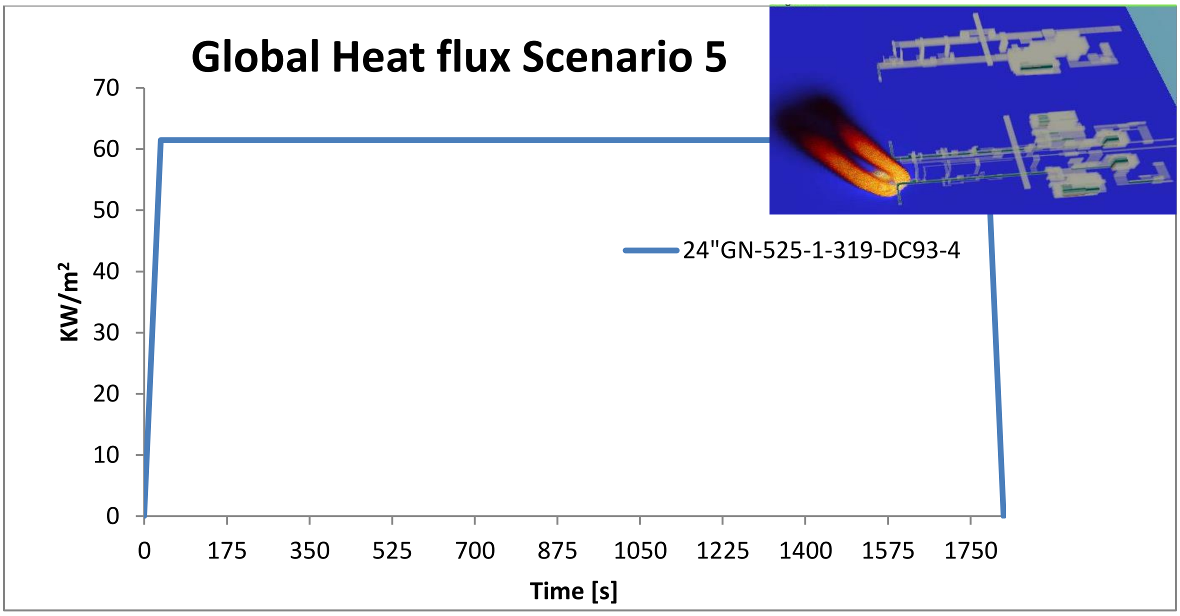


Graph 5 Scenario 3; Peak heat fluxes.

The value of peak heat flux is given to the following pipes: 24"GN-525-1-315-DC93-5/6 and 3"GN-525-1-320-DC93. Peak heat flux in Graph 5 is stabile in the range of 325 kw/m^2. These 3 pipes are located close to the leak origin, which lead to a engulfing in fire.

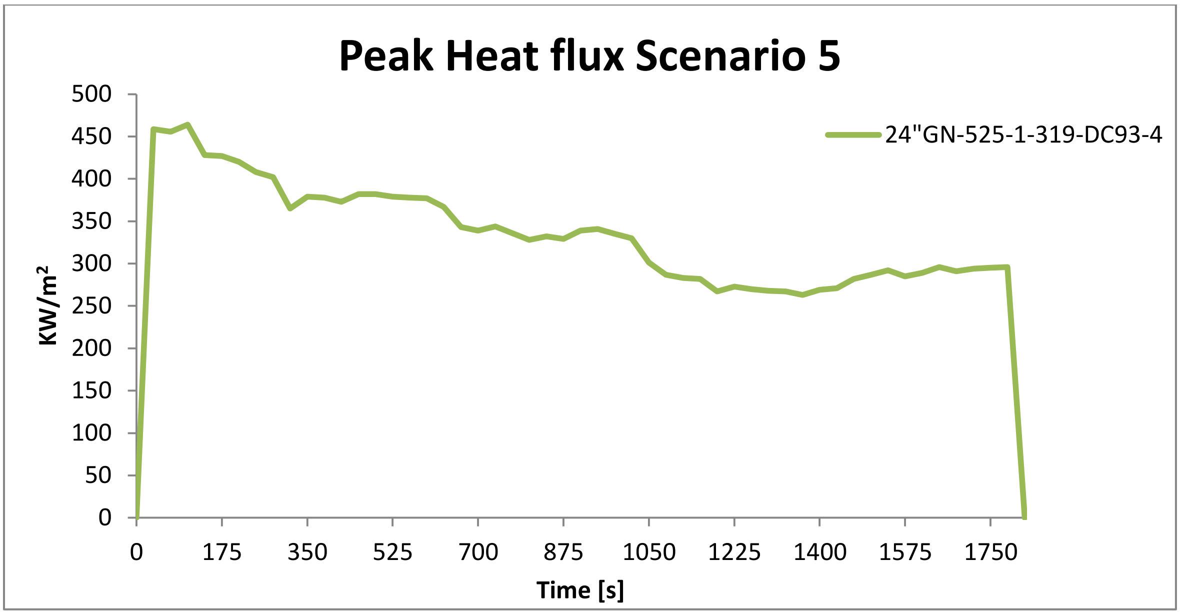
5.1.3 Scenario 5, directed into the ground.

In this section both the global and peak heat flux for the most affected pipe in scenario 5 will be presented. Only one pipe is exposed with a mentionable value for flux. This occurs due to the jet fire's behaviour, as well as the wind direction, leads the jet fire away from the process trains.



Graph 6 Scenario 5; Global heat fluxes.

The curve 24"GN-525-1-319-DC93-4 is constant as long as the initial leak is active, due to its position relative to the initial leak and the jet. This phenomenon will be discussed in chapter 7 "objects works as flame stabilizers".



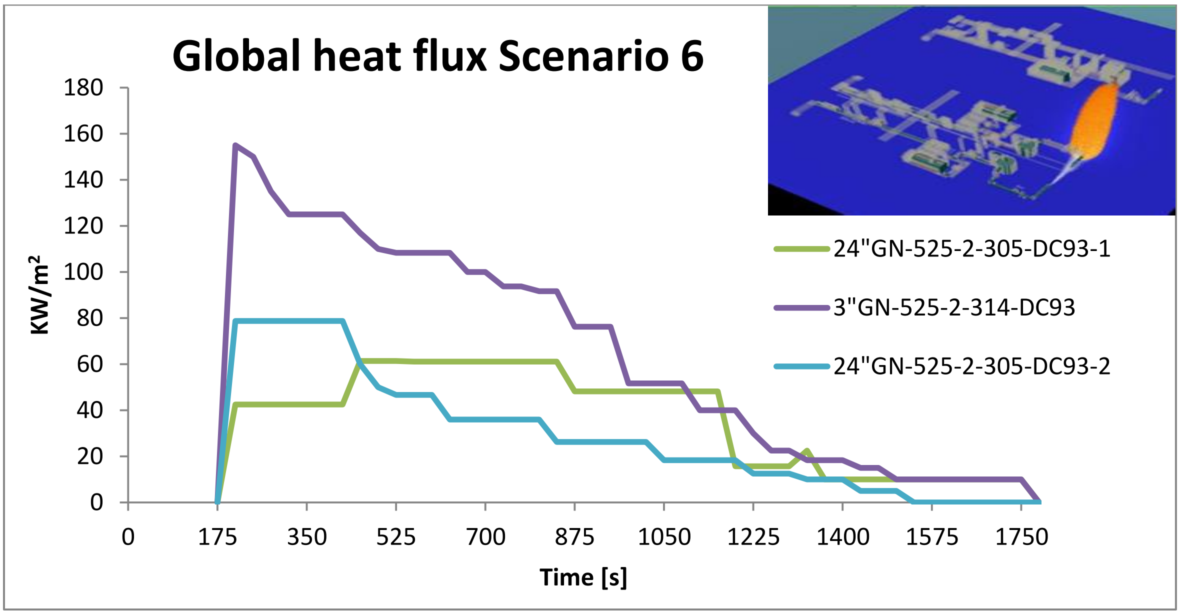
Graph 7 Scenario 5; Peak heat fluxes.

The peak heat flux is in the range of 450 and 300 kW/m^2 throughout the simulation, and is slightly decreasing.

The scenario is simulated through phase one. However, the scenario will not be simulated in second phase, because of two reasons; its difficulty to assess if the peak heat flux is on the ground or on the pipes underside (due to how the geometry is drawn) and second, no rupture is recorded.

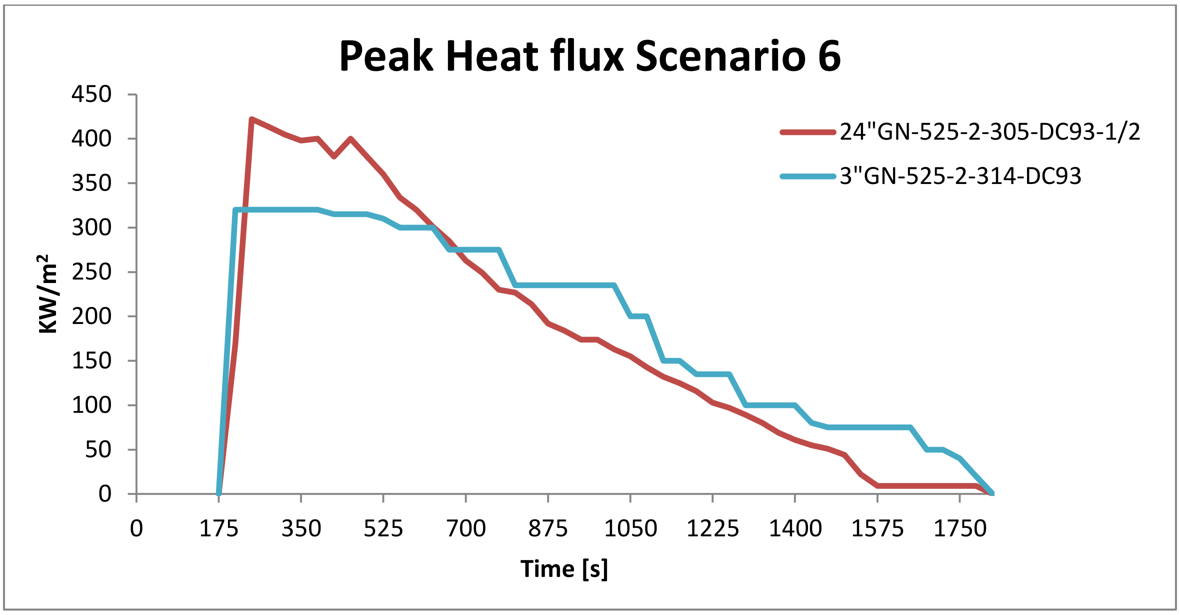
5.1.4 Scenario 6, ignition delay high release flow.

The initial leak in scenario 6 takes place on train 1 and only affects train 2 with a starting flow of 7.5 kg/s. Heat fluxes found from scenario 6 is presented in this section, starting with global heat loads:



Graph 8 Scenario 6; Global heat fluxes.

The curve for the 3” pipe decreases almost linearly. With a highest value in the range of 160 kW/m^2 and due to the ignition delay the values for flux first starts after 175 seconds. The green curve is slightly increasing the first few minutes, until it reaches its highest value of 60 kW/m^2 and further decreases.



Graph 9 Scenario 6; Peak heat fluxes.

The curves are similar to each other. The 24” pipe curve has a higher peak flux with a value of around 420 kW/m^2 for a short period of time. After 700 seconds the peak flux for the 3” pipe exceeds the value for the 24” pipe.

5.2 Second phase, does escalation occur?

Every ignited simulation registered rupture, except scenario 4 and 5. Scenario 1 and 6 recorded rupture in a 3” pipe (3”GN-525-2-314-DC93), a rupture in this pipe is assumed to cause a jet to form and targeting the pig receiver area. However, this is not in the geometry used.

Scenario 2 and 3 are chosen for the second phase, both recorded rupture on the same train as the initial leak. In scenario 2 (directed toward heat exchanger) the escalation occurred in a 2“ pipe (2”GN-525-2-318-DC93), here two directions will be evaluated.

In the first direction both the jet fire and wind is targeting train 1 (east, Figure 18), whereas the jet fire will have a -15 degree angle. The other direction is in the opposite direction as the initial leak (north), with the default value of wind (the winds direction is 7 m/s south west). Both directions are shown below:

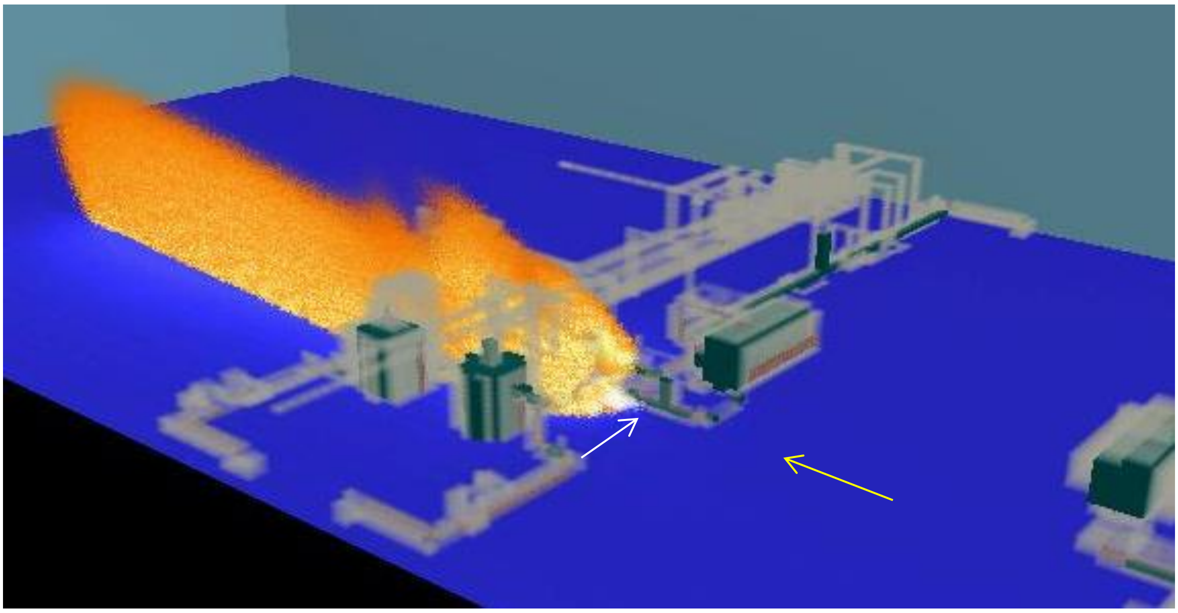


Figure 18 Scenario 2; 30 seconds after rupture in a 2" pipe, direction east.

Release flow in Figure 18 is 21.9 kg/s embracing parts of train 1. The length of the jet is approximately 60 meters. The white arrow represents the initial leak and the yellow represent wind direction.

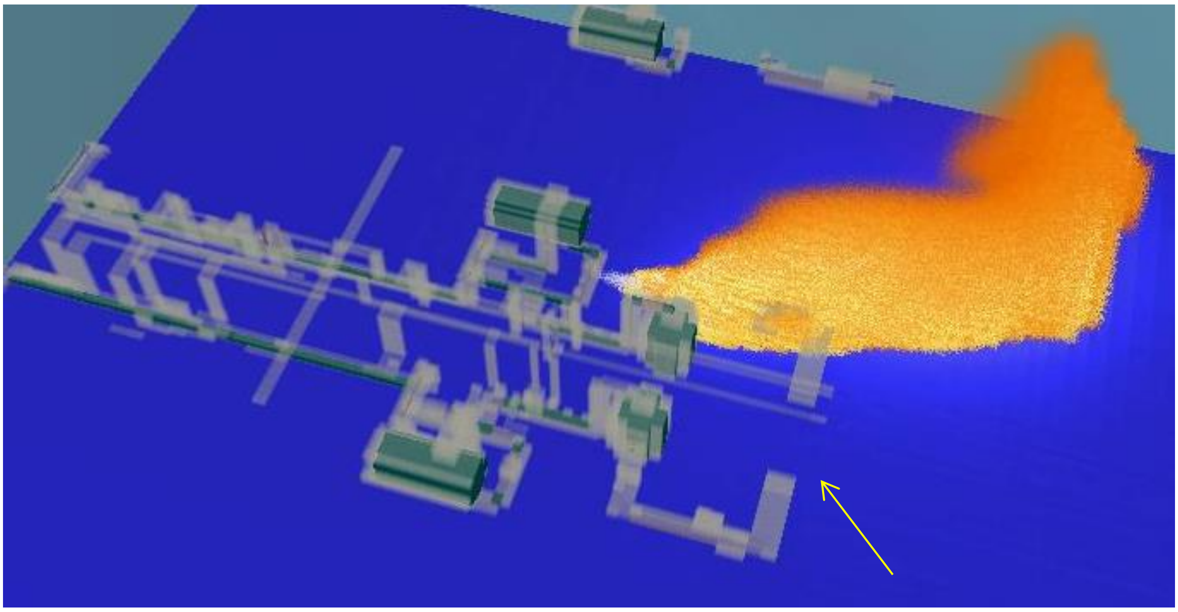
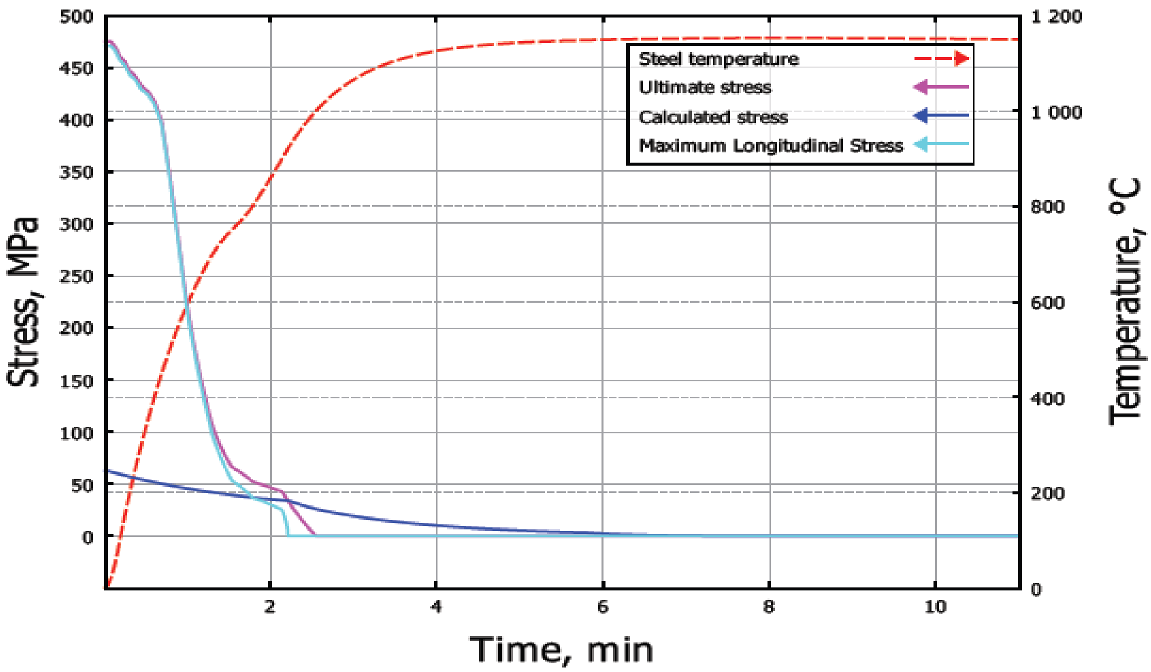


Figure 19 Scenario 2; 27 seconds after rupture in a 2" pipe, direction north.

Release flow in Figure 19 is 22.8 kg/s. The length of the jet is approximately 40 meters

To set Figure 18 and 19 in proportion; a train is approximately 60 meters. In Figure 18 the jet is longer, this is partly because the wind direction is the same as the jet fire. Figure 19 is shorter and the wind will affect the end of the flame, because of the momentum of the jet is decreasing the longer from the source it gets. Yellow arrow represents wind direction.



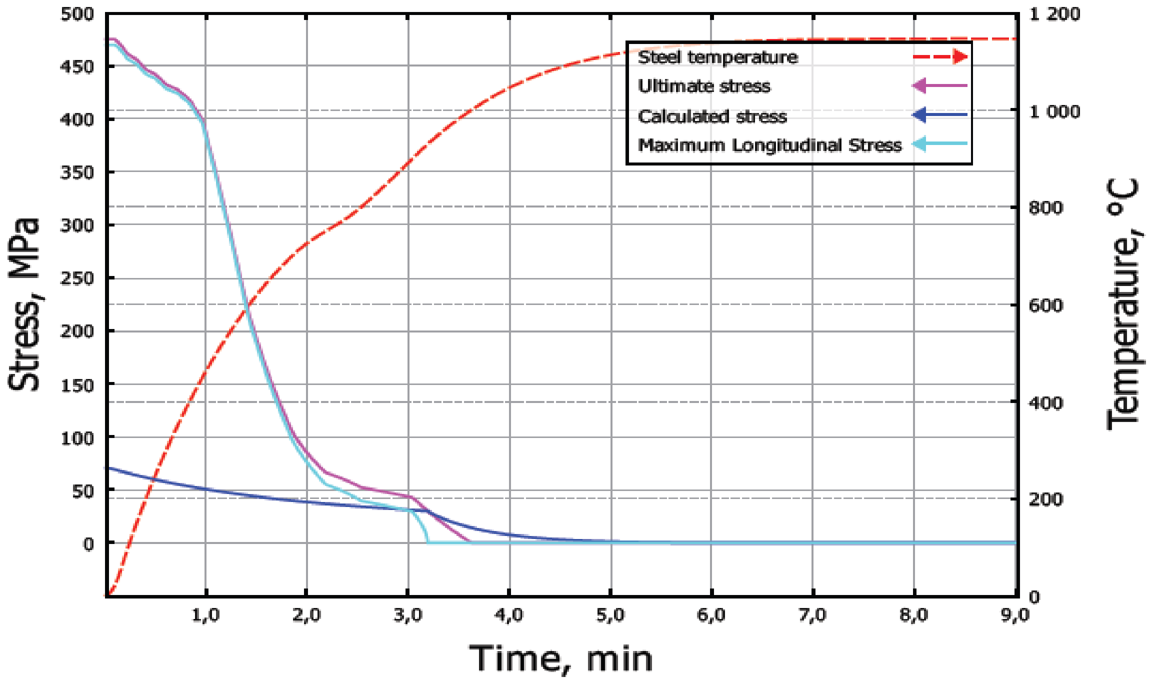
Graph 10 Scenario 2; Stress curve 2"GN-525-2-318-DC93, second phase.

A short description of Graph 10:

For each time step the stress is calculated based on the pressure inside the object (vessel or pipes) and the objects dimensions (the blue curve). The calculated stress is compared to the rupture criteria. The rupture criteria can either be the maximum longitudinal stress or the ultimate tensile stress (UTS) at the elevated temperature, depending on what is specified in the input. In these simulations the ultimate stress curve is defined as the rupture criteria. If the calculated stress exceeds the acceptance criteria, the object shell is assumed to disintegrate [16]. The difference between ultimate stress (strength) and longitudinal stress (load) is that ultimate stress is dependent on temperature and longitudinal stress shows the remaining strength in the pipe, longitudinal stress gives the stress affected on the pipe including stress caused by inventory. As every stress graph shows, when the ultimate stress curve exceeds the rupture criteria and rupture is indicated, the longitudinal stress curve goes to zero (no remaining strength).

Graph 10 indicates rupture in the 2 inch of diameter pipe after 130 seconds (2.16 min).

The next scenario to be studied is scenario 3, where rupture occurs in a 3” pipe (3”VA-543-1-312-DS93) on train 1.



Graph 11 Scenario 3; Stress curve 3"VA-525-2-312-DS91, second phase.

Graph 11 gives time to rupture for the 3” pipe to be around 190 seconds (3.16 min). The direction of the rupture is positive Z (up). The values for heat flux is pre-defined, a rupture will therefore not affect the temperature development in “its specific/personal” simulation. Example, Graph 11; Rupture in a 3” pipe, will not ignite in Vessfire. To evaluate the contribution of the 3” rupture KFX have to be used.

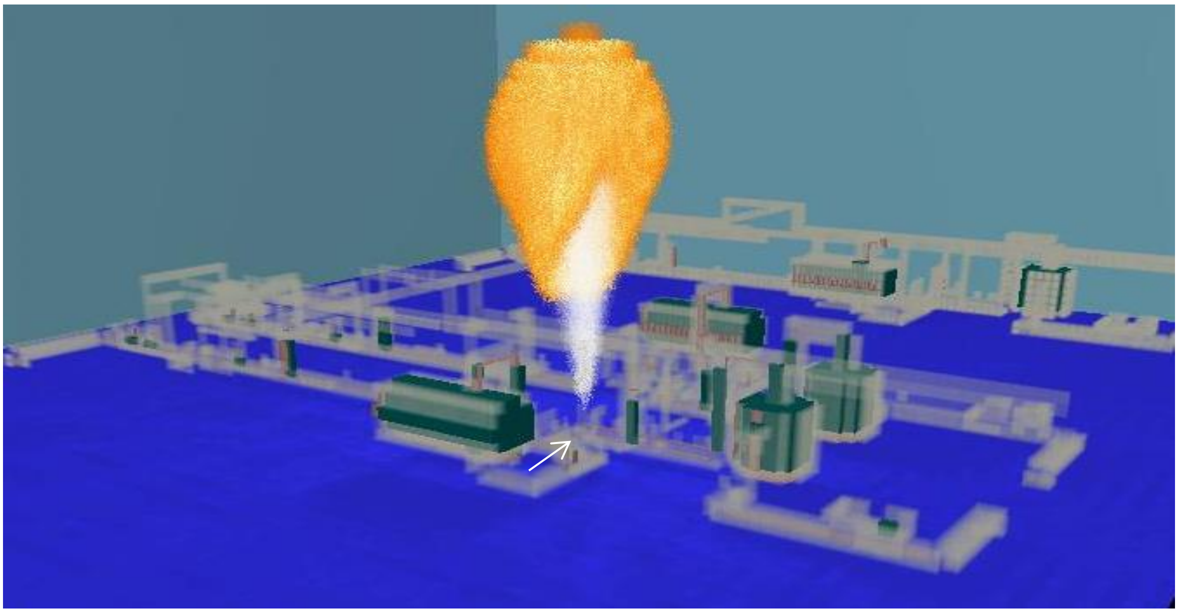
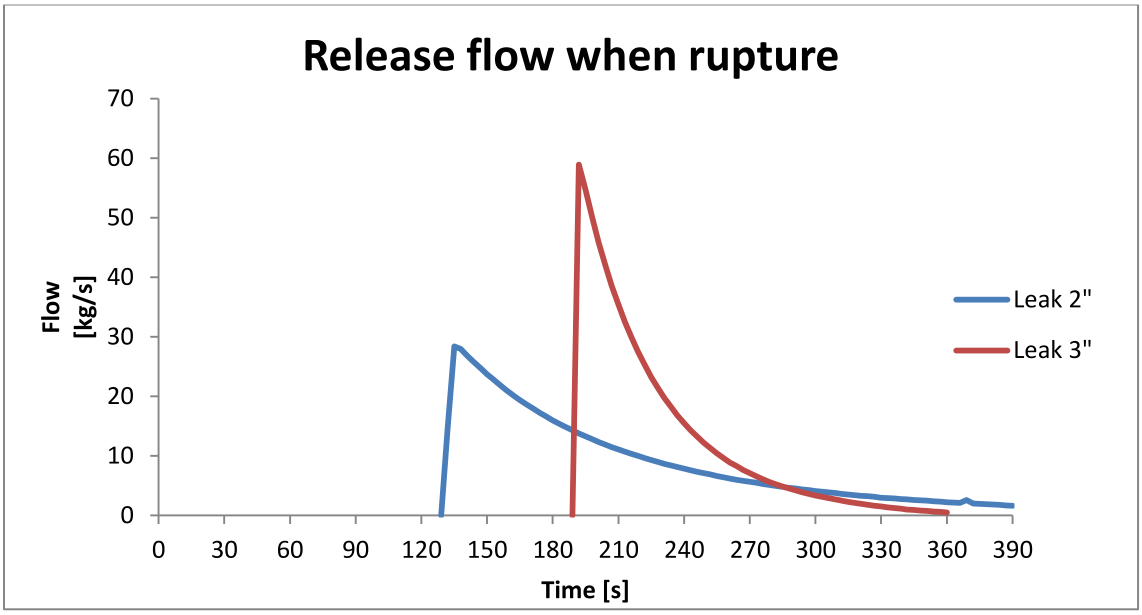


Figure 20 Scenario 3; jet fire 2 seconds after rupture in a 3" pipe.

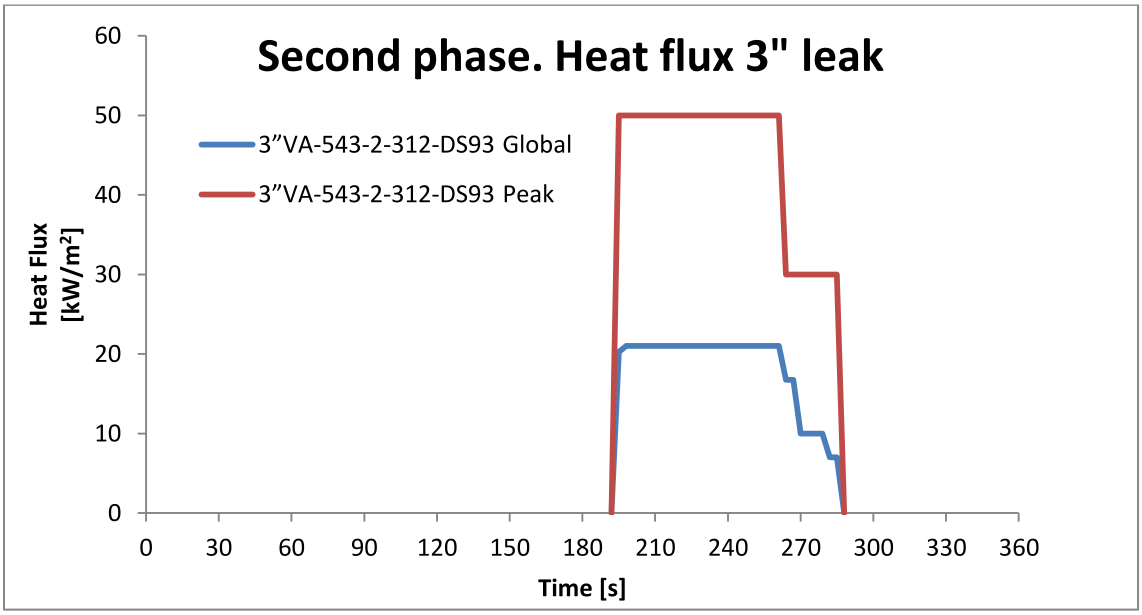
Scenario 3, leak from train 1; Release flow in Figure 20 is increasing and is therefore difficult to give an exact value for flow. However, after 3 seconds the value will be 54.7 kg/s. The length of the jet is approximately 30 meters. White arrow represents the initial leak.

Using Vessfire in the first phase the following curves are found, and are used in KFX to evaluate further escalation to other segments. KFX will due to large simulation time only simulate a single event at a time (this will be explained and discussed in chapter 7).



Graph 12 Release flow when rupture, second phase.

Graph 12 illustrates how the release flow upon rupture will behave. Peak value is time limited and will decrease fast, as well as the mass and pressure in the segment. The curves are from 2 separate scenarios (leak 2", scenario 2 and leak 3", scenario 3). The release flow upon rupture gives a large contribution to the leak, the pressure remaining in the segment when rupture occurs is respectively 47.26 barg and 64.26 barg for the 3" and 2" leak. For the 3" leak (scenario 3) the heat fluxes is small, here shown for one of the most exposed pipes[5]:

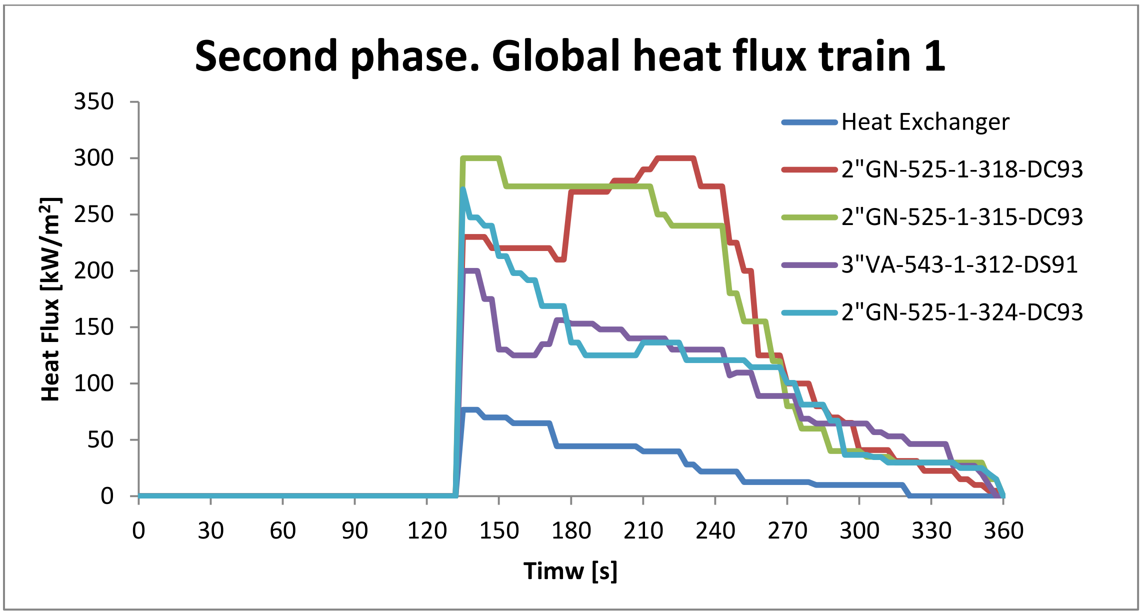


Graph 13 Scenario 3; Second phase, heat fluxes 3" leak

[5] There is reason to believe that there were higher values for heat flux, however not every pipe is drawn into the geometry.

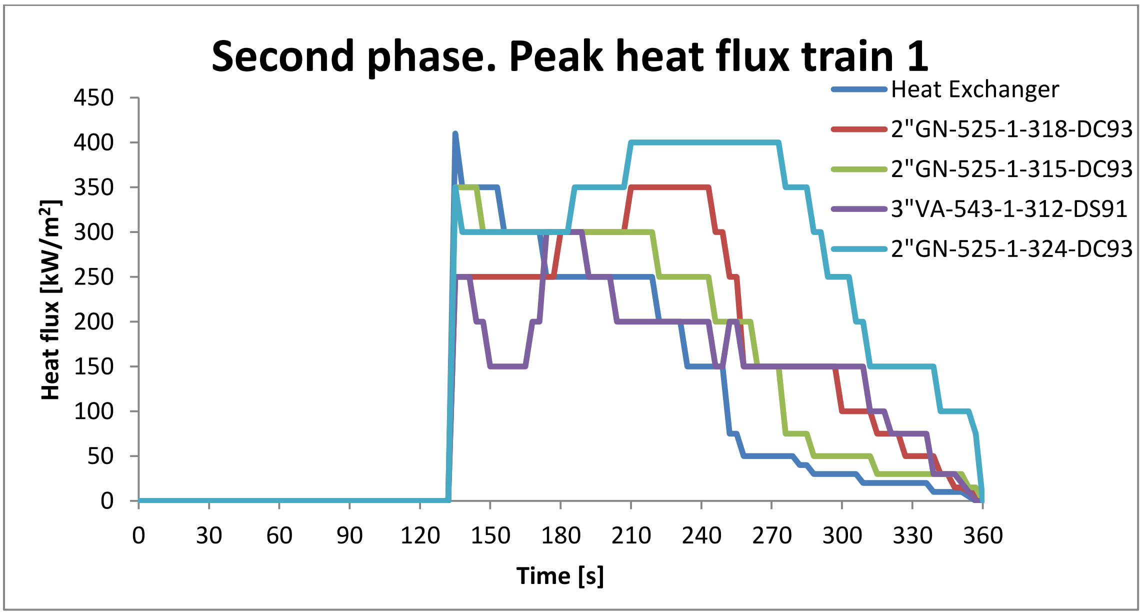
The graphs shows a low influence of heat flux and this will therefore not be simulated in Vessfire, It is likely to say that no rupture will occur within this range of heat flux.

The following heat fluxes are found in KFX after simulation with the 2” leak (scenario 2), and will be simulated in Vessfire:



Graph 14 Scenario 2; Second phase, global heat fluxes train 1.

These values for global heat fluxes will for some pipes increase as the rate of the rupture decreases, this phenomenon will be briefly discussed in chapter 7. Some of the pipes are exposed to a global heat flux in the range of 300 kw/m^2 as long as a couple minutes.



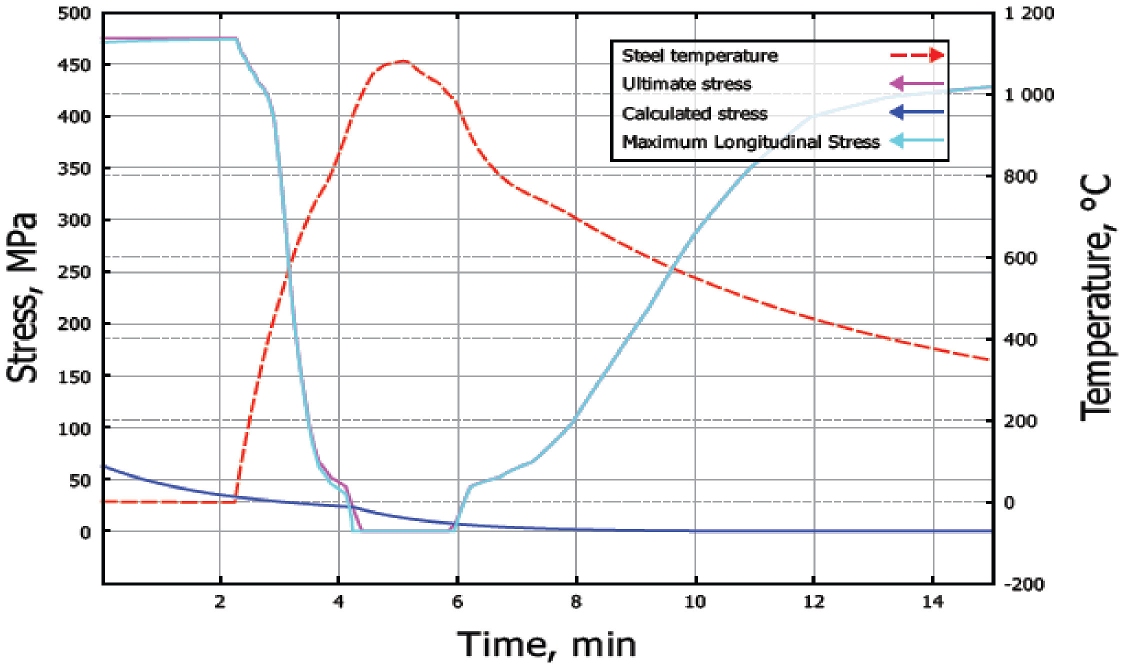
Graph 15 Scenario 2; Second phase, peak heat fluxes.

As the global loads increase, so do some of the peak loads when the release flow decreases. The highest value of heat flux is limited to a short period of time, but is as high as 400 kW/m^2 for two of the curves. For the 2”GN-525-1-324-DC93 it will be 400 kW/m^2 for around 1 minute.

5.3 Third phase, escalation to another train?

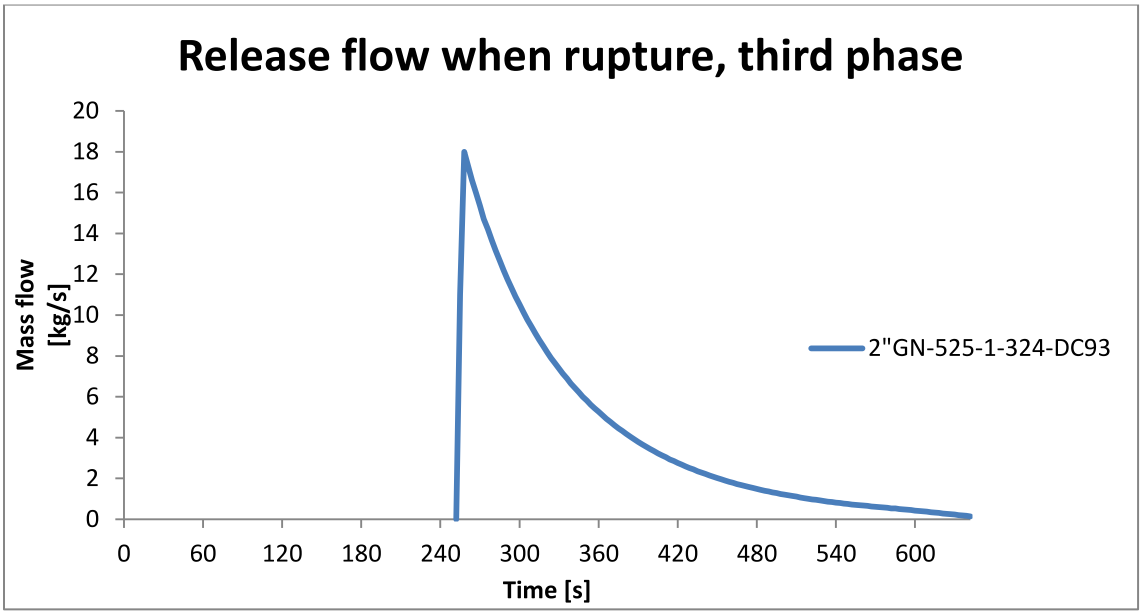
This section will only document any further escalation, with position, leak flow in rupture, remaining pressure in the segment etc.

In scenario 2 the first recorded escalation occurred on the same train as the initial leakage. This rupture in an 2” pipe (2”GN-525-2-318-DC93) and its direction is directed towards train 1 resulting in a further escalation, and rupture in a 2 “ pipe (2”GN-525-1-324-DC93) connected to the first of 2 SSV on train 1. Therefor 2”GN-525-1-324-DC93 marks the beginning of the third phase.



Graph 16 Scenario 2; Stress curve 2"GN-525-1-324-DC93, third phase.

Graph 16 indicates rupture after approximately 4 minutes (240 sec). The sudden drop in temperature is due to the thermal exposure on the pipe stops after 6 minutes (360 sec) see Graph 15. When rupture is assumed on 2”GN-525-1-324-DC93 (located on train1), BD has been initiated and the depressurization process has already been active for 4 minutes. As the scenario starts on train 2, there will be no initial leak on train 1. The only way of depressurization will therefore be BD, should rupture occur will also the rupture have a depressurization effect on the segment.



Graph 17 Scenario 2; Release flow when rupture 2"GN-525-1-324-DC93, third phase.

Graph 17 shows a peak value of 18 kg/s decreasing rapidly. The flow will reach zero 400 seconds after rupture occurs.

When rupture occur the remaining pressure and mass in the segment is 43.9 barg and 2230 kg gas and 95 kg gas.

Simulation results in Vessfire indicate that some amount of liquid will be formed in the segment, this phenomenon will be briefly mentioned here and further discussed in section 5.5. Liquid will typically be formed where the expansion is largest (around the blowdown orifice), and some amount of liquid would therefore be transported throughout the vent line. This is a complex phenomenon to calculate, and Vessfire does not calculate the amount of liquid leaving the segment.

5.4 Gas dispersion:

Calculated by KFX the value of LEL is approximately 4.7 vol % and UEL 14.6 vol % with the gas composition used. Figure 21 and 22 are after 70 seconds and figure 23 and 24 are after 455 seconds (same scenario). All other figures in this simulation are similar to the one shown.

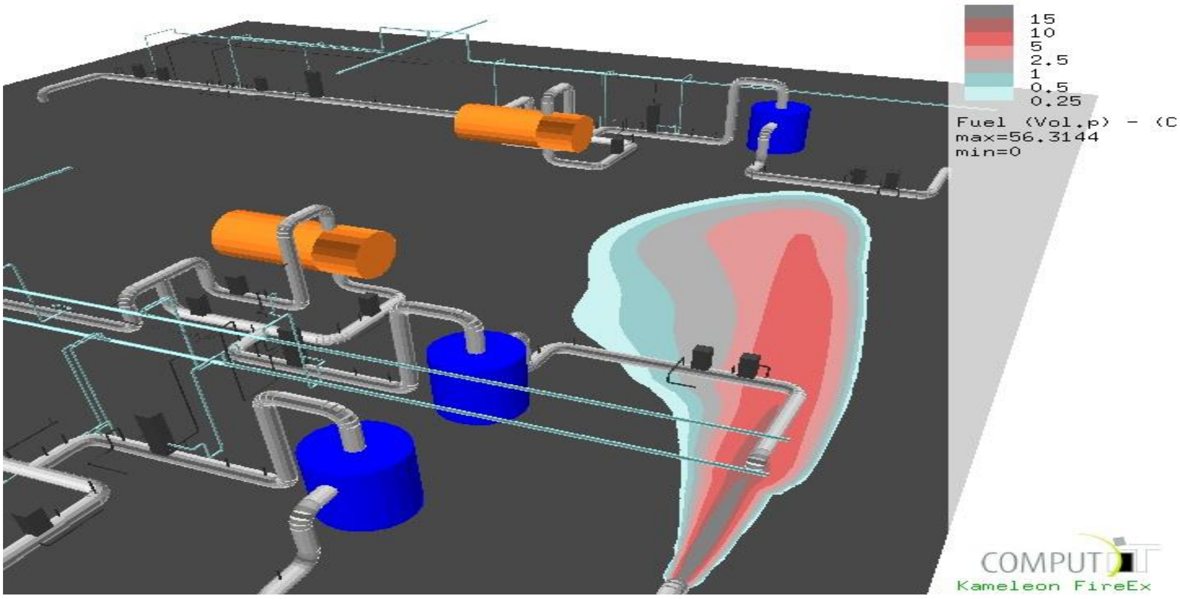


Figure 21 Gas dispersion after 70 seconds.

The release flow in Figure 21 is 6.8 kg/s, and a small gas cloud is formed. The reach of the explosion limit (LEL) is almost as long as the gas cloud. This is still early in the dispersion and the area of LEL and upwards is covering the majority of the cloud.

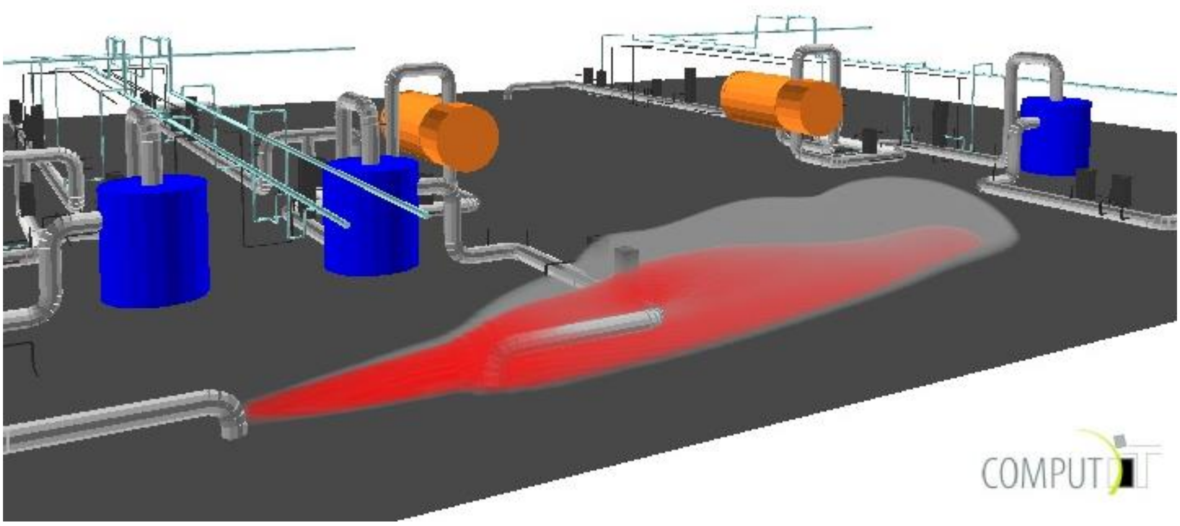


Figure 22 LEL rendering after 70 seconds.

The area of LEL will reach a height of about 2 meters after 70 seconds (Figure 22). The start of the grey area is where the exact value of LEL is and the red area is 2*LEL and upwards. This means closer to red area, closer the gas compositions is 2*LEL.

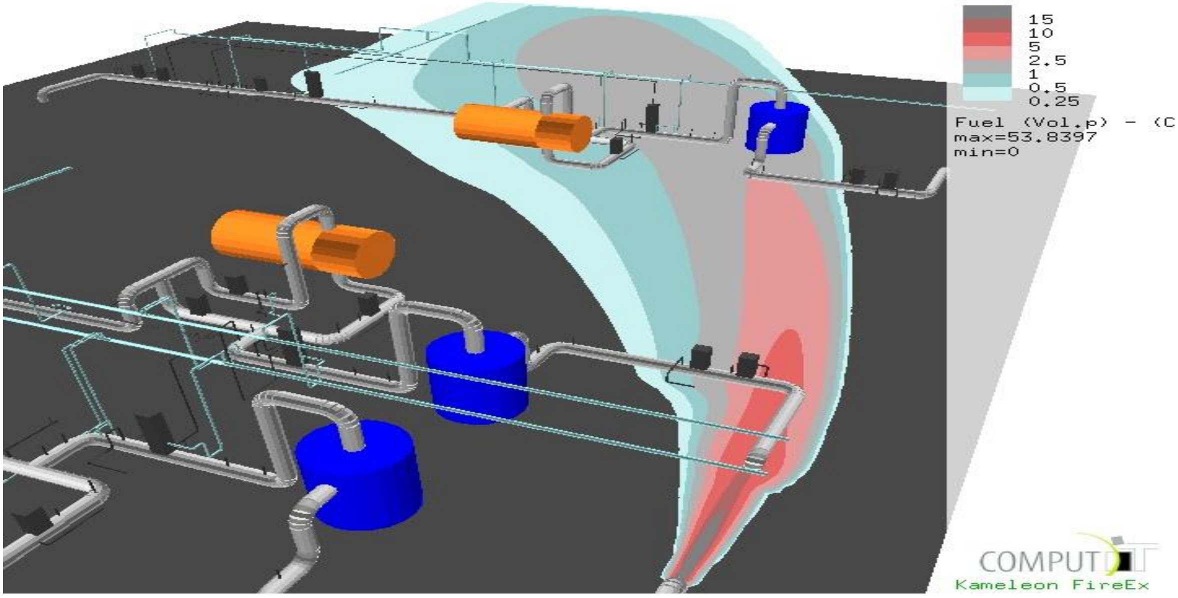


Figure 23 Gas dispersion after 455 seconds.

The release flow in Figure 23 is 4.2 kg/s after 455 seconds, and the range of the cloud is larger than in Figure 21 and 22, the reach of the area inside LEL is similar as for 70 seconds. However, its reach is a few meters longer. Figure 23 also shows the clear effect of the wind forcing the gas dispersion in the same direction.

The area of LEL and upwards is now only a minor part of the gas cloud, a low volume % of gas is no engulfing train 3.

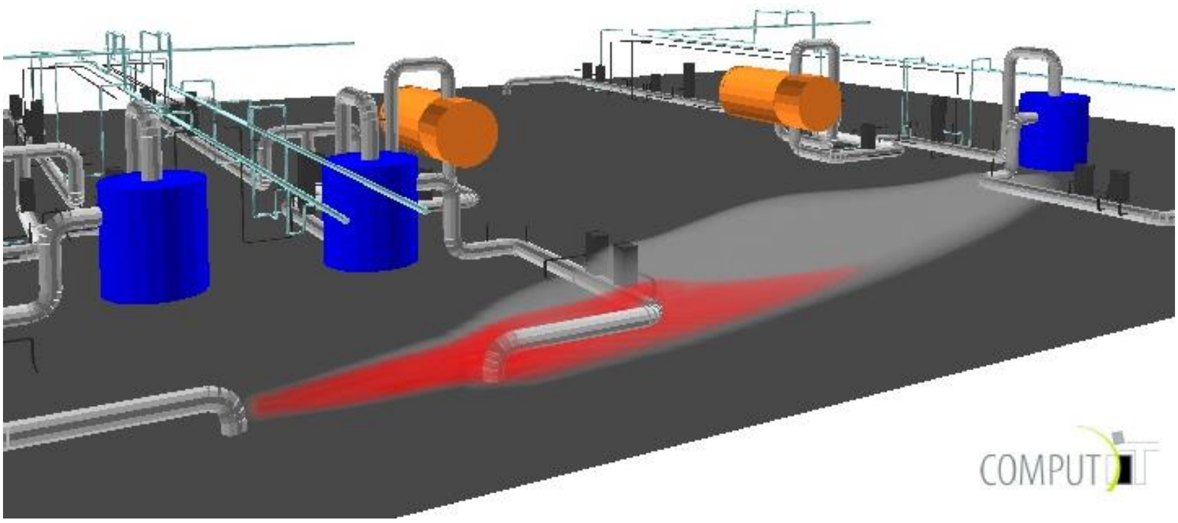
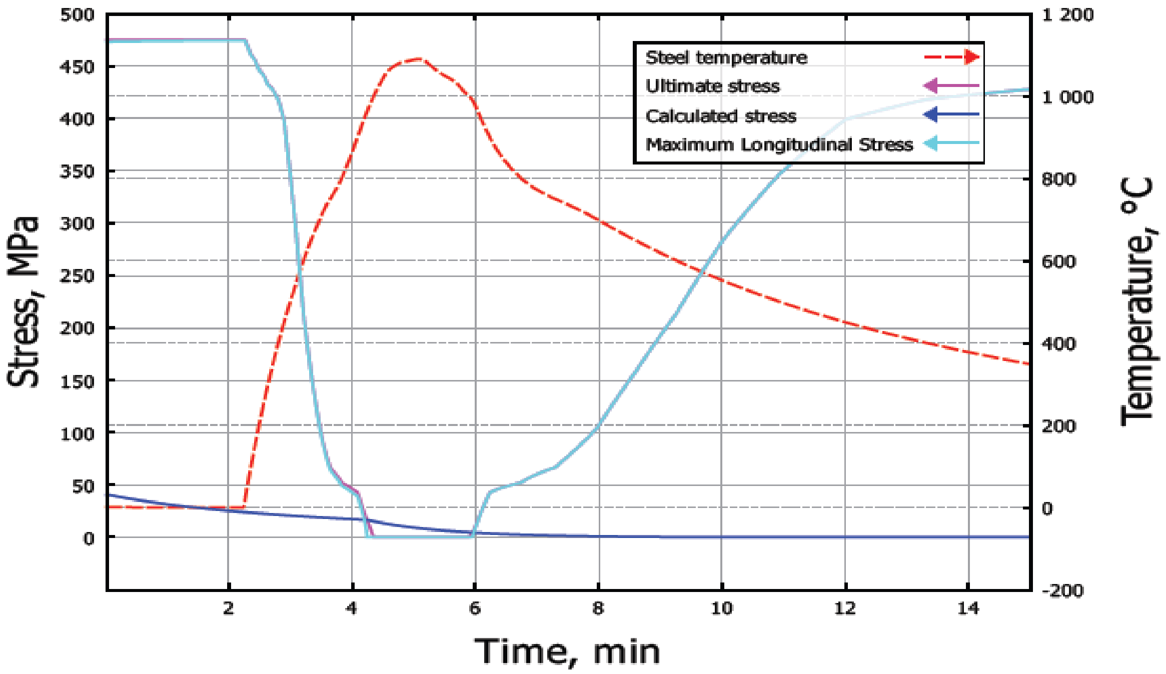


Figure 24 LEL rendering after 455 seconds

The grey area reaches further than after 70 seconds. However, the height and the red area are smaller. It looks like as the flow decreases as does the area with a high volume % of gas.

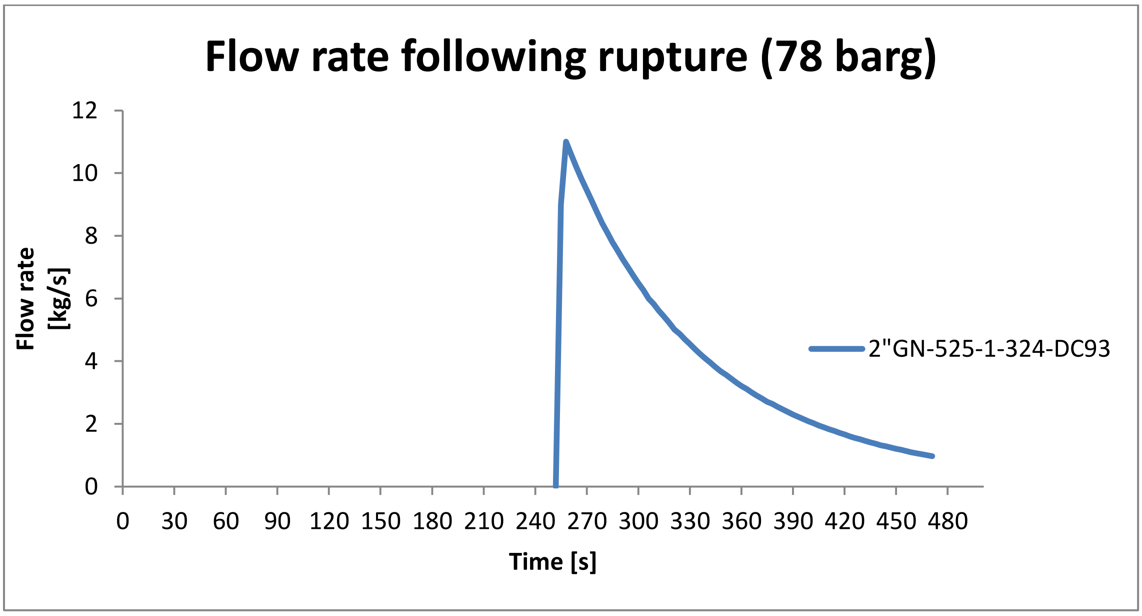
5.5 Simulation with 78 barg in segment

In this section scenario 2 “directed towards heat exchanger”, third phase will be simulated with 78 barg pressure.



Graph 18 Stress curve 2"GN-525-1-324-DC93 78 barg

The calculated stress curve starts at a lower value compared to the rest of the results curves for calculated stress. Rupture is assumed after 4.1 minutes. Remaining pressure and mass in the segment is 31.23 barg and 1308 kg gas and 25 kg liquid.



Graph 19 Flow rate following rupture (78 barg).

Graph 19 shows a peak value of 11 kg/s decreasing fast, the rate will reach zero around 250 seconds after rupture occurs.

The result will be further discussed in chapter 7, whereas the simulation with 78 barg will be compared to the simulation with 120 barg.

5.6 Discussion escalation study

In part 1 of the thesis, eight different scenarios were chosen to assess if escalation occurred with the implemented safety measures, assuming that they functioned as intended.

The reason why gas could be so hazardous, are due to process conditions handle gas under high pressure, and for the main part of the composition (especially methane) at temperature above normal boiling points.

The initial leaks for the chosen scenarios were in the range of 2 to 7.5 kg/s, whereas scenarios with leak flow of 2 kg/s affected several pipes of smaller dimensions. Every leak was simulated with a transient leak flow, and own defined heat loads (through simulation) where found by visual observation. The purpose with an own defined heat load is to get a more realistic picture of the leak and jet fire, and a better understanding in how a hazardous event will develop.

The simulation process went over 3 phases, where the initial leak was the first phase. The scenarios with 2 kg/s leaks only recorded rupture on the same process train as the initial leak. A reason for that could in some degree be the direction of the leak, wind or geometry. While the scenario with 7.5 kg/s, were the only case that recorded rupture on another train. The scenarios with 7.5 kg/s have almost the same direction as the wind and hence a higher calculated length. The length between train 1 and 2 is around seven meters. Given another leak origin and scenario for a leak in the range of 2 kg/s it is likely to believe that escalation from one process train to another is possible.

As mentioned earlier, all scenarios except scenario 4 and 5 indicated ruptures. In scenario 4 the distance between train 2 and 3 is 20 meters and the leak flow is quickly decreasing. The recorded heat fluxes on train 3 were minor. The jet fire in scenario 5 is directed into the ground and the wind is leading the gas/jet fire away from nearby pipes, causing insignificant amounts of radiation exposing nearby pipes. The ground functions as a flame stabilizer, stabilizing the heat flux (both peak and global). Due to wind direction will the value for global heat load stay minor. The phenomena where objects works as flame stabilizers were present in several scenarios, in scenario 3 the leak is directed into an 24" pipeline underneath the heat exchanger on train 1 and in some degree crushes the jet. When the jet loses large amount of impulse it will decrease in length and increase in diameter. The exit velocity for the flow will decrease slowly compared to the leak flow (as the pressure decreases). This could contribute to higher values of heat flux on nearby pipes, over a longer period of time. Another reason for high values for heat flux is due to a larger contribution of convective heat transfer, not just radiation.

The value for peak load in scenario 5 is in the range of 450 kW/m^2 (which is high). It is difficult to evaluate the heat load on the pipes underside due to how the geometry is drawn (with a plate on ground level to be sure KFX simulate this as the ground). This is the reason why the highest value registered in this scenario, is set to the peak value used to expose affected pipes throughout the simulation in Vessfire. The result was no rupture on the 24" pipe.

When rupture occurred on a 2 or 3" pipe the depressurization of the segment increased rapidly, which is logical. Due to a large amount of mass released in a short time period. For the 2" rupture (scenario 2 second phase, direction east from train 2) the jet actually passes the most of train 1 because of its high release rate and velocity. It is first when the flow decreases that the jet embraces parts of train 1. Thus the values for peak and global heat load for some pipes will in this scenario increase in the beginning as the flow rate decreases.

For Scenario 3 third phase, rupture occurs in a 3" pipe directed upwards. Due to the jets direction and high release flow (around 60 kg/s for a short period). The rest of the plant is only exposed to a minor amount of heat radiation, resulting in no further rupture. Even when the release flow decreases, and the jet fire (combustion zone) comes closer to objects, the quantity of incoming radiation on objects keeps on a low level. The process train was due to the high release in the rupture depressurized extremely fast and the accident did not further escalate. This actually means that the 3" rupture had some positive effect.

Simulation of gas dispersion (section 5.4) shows that a small gas cloud is formed, this only when there is an on-going leak. When the release flow decreases there is minor differences in the area of LEL, it actually increases for some time. A reason for this could be high velocity in the jet or large loss of impulse, when the jet hits the 24" pipe. Causing a more efficient dispersion, and when the flow decreases so does the loss of impulse, due to a lower exit velocity. And the jet has a high concentration level out of the leak origin

Reference plant has a zero policy (recommended practice RP) for ignition sources on the process site. This means, no ignition sources should be present in the area of hazardous material. The range of LEL will for some time be around 30 meters, and cover some of the area between train 2 and 3. Should an ignition source be present at the same time as a sufficient large enough leak, then it is likely for an ignition to take place.

Reference plant is built in a flat and windy area, it is thus reasonable to say that the rate of natural ventilation is high. There are also no major obstacles, so it is unlikely for gas to be trapped/present any other place except around the actual leak.

Every leak origin is simulated as a circular hole. Leak through a circular hole may have a different exit direction/form, compared to leak through a crack. It is reasonable to believe that a leak through a circular hole have a longer length, then a leak through a crack when it is not affected by objects (due to how the jet is concentrated through the hole and towards a direction). However, there are no results in this thesis, which predict how a jet fire through a crack will develop when affected by or directed into other objects.

To summarise the results; Rupture is indicated to occur for smaller pipes (typically up to 3 inch of diameter). When affected by a peak heat flux over 300 kW/m^2 over a short time period (2 to 3 minutes), this will in some degree be independent on the size of the leak. This time perspective would in many cases be before blowdown is initiated. NORSOK S-001 [1] states that the flare system shall maintain its integrity during DALs for the required period of time, in some of the simulations (for example scenario 3) conducted in this thesis some of the lines leading to the vent stack will rupture, due to exposure by heat over a given period of time. And in that case this statement from [1] will not be fulfilled for the mentioned simulation in this thesis.

5.6.1 Phase shift discussion

Simulation results in Vessfire states that some amount of liquid is formed as a product of depressurization. When a segment is depressurized the remaining mass will expand. The effect of the expansion is assumed highest around the flow orifice. When the gas composition expands the temperature decreases rapidly. This is a well-known effect that affects typically the vent lines. This phenomenon is called Joule Thomson effect. The effect is largest where/when the flow rate is highest (when the depressurization is most rapidly). As the backpressure in the segment and the flow decreases so will the Joule Thomson effect. Having a cold medium flowing inside exposed pipes could have positive effect, due to the cooling. This expansion may also result in a phase shift, some amount of gas condensate to liquid depending on gas composition. For some of the simulation conducted in Vessfire presented in chapter 5 and 6 the amount of liquid remaining in the segment when rupture occurs is approximately 180 kg. The gas composition processed in reference plant consists mainly of methane. Will it be reasonable to believe that a so high amount of liquid is formed in the segment?

Table 5 Amount of mass.

Gas	Boiling Point	Molecular weight	Mol	Initial kg gas
Methane	-160 ℃	16.04 [g/mol]	246535.75	3954.4
Ethane	-89 ℃	30.07 [g/mol]	15883.12	477.6
Propane	-42 ℃	44.09 [g/mol]	4224.4	186.25
Butane	-1 ℃	58.1 [g/mol]	1375.75	79.93
Pentane	36 ℃	72.15 [g/mol]	330.2	23.82
Hexane	68 ℃	86.19 [g/mol]	165	14.22
Heptane	98 ℃	100.18 [g/mol]	82.5	8.26
Octane	125 ℃	114.18 [g/mol]	16.5	1.88

The amount of methane and ethane is around 95 % of the total mass, this is also the two gases with lowest boiling point. These two gases summarized gives a total weight of 4432 kg, summarizing the rest of the gases gets the weight of 315 kg.

From Vessfire results, the phase shift starts typically after one to two minutes depending on the rate of depressurization, and will shortly after reach its highest value. In some cases the amount of liquid will increase after the decreasing has started, typically when rupture occurs or a new BDV opens. This will be a result of an increase in depressurization. Through Vessfire the largest contribution of liquid is shifting between propane, butane, pentane etc. This is at the end of the simulation. In the start methane and ethane constitute the largest amount of liquid, this is only for a short period of time (When the Joule Thomson effect is largest). In some cases the gas temperature will be as low as -100 ℃ , this is still 60 degrees over methane's boiling point, why gives methane a large contribution to the amount of liquid in the beginning?

The reason must be linked to methane's critical point, every gas has a given value for temperature, which is the highest value of temperature (called critical temperature) where the gas can condensate an take liquid form. The lowest value of pressure then needed is called critical pressure. When these two criterias are met, the gas is located in its critical point [24]. For methane the critical temperature is – 86 ℃ and the critical pressure is 45 bar and upwards. This means that methane doesn't need to get under -160 ℃ (this value is set for atmospheric pressure) to condensate to liquid, it actually needs to get under – 86 ℃ when the pressure is 45 bar. The pressure in the process segment starts at 120 barg. For ethane, propane and the rest of the gases in the composition it will be similar values for critical temperature and pressure.

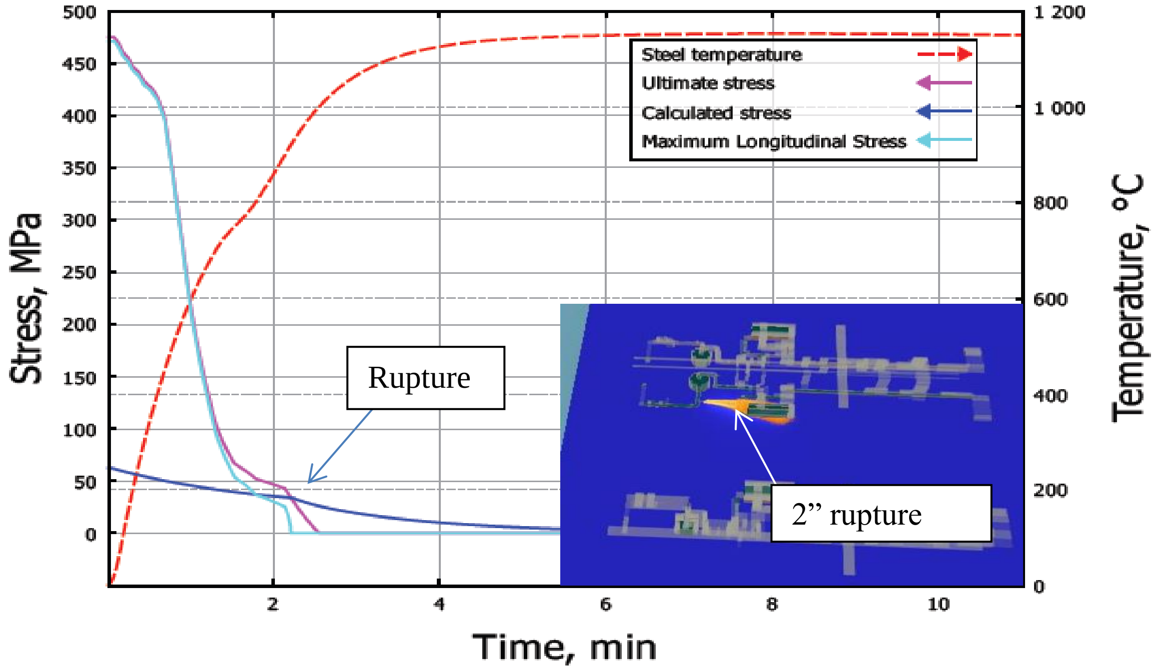
6 Risk reducing measures

This chapter will present risk reducing measures and their effect.

There are two types of risk reducing measures, active (AFP) and passive (PFP). AFP is equipment or system, which by being activated can control or extinguish/stop an unwanted event such as fire. PFP can be structural measures or cladding arrangement, which in the event of fire will provide thermal protection for vulnerable locations or buildings.

Risk reducing measures evaluated in this thesis are use of insulation, increased rate of depressurization, increased flow and sequential depressurization and increased wall/shell thickness.

The comparison/reference case is the stress curve from scenario 2 “directed towards heat exchanger”, first phase (2”GN-525-2-318-DC93). Time to rupture as well as mass and pressure inside the segment when rupture occurs will be compared to data from simulations with risk reducing measures. The heat load exposing the pipe is shown in graphs 2 and 3 (page 30) in chapter 5. Incoming heat flux will be the same in every example. Scenario 2 is chosen because this is the only scenario which goes over all 3 phases, and escalates from one process train to another.



Graph 20 Stress curve comparison criteria 2”GN-525-2-318-dc93.

Rupture is indicated after 2.22 min (133 seconds), remaining pressure inside segment when rupture occurs is 64.26 barg and the mass is 3271 kg gas and 30 kg liquid, the amount of liquid is a bi- product of fast depressurizing (phase shift). The sudden drop in the curve for ultimate stress after around 2 minutes is due to the high temperature (around 1000°C). The white arrow marked 2” rupture, marks the location of pipe 2”GN-525-2-318-DC93.

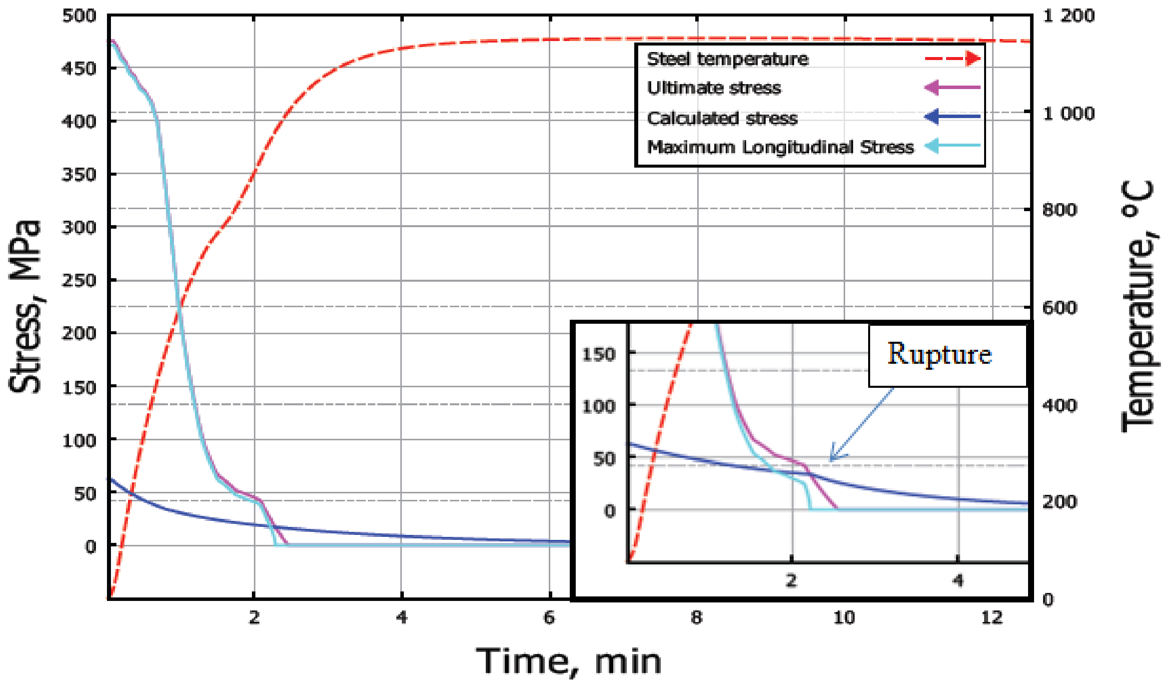
6.1 Blowdown

The purpose with blowdown (depressurization) systems is [1]:

- In the event of fire to reduce the pressure inside a process segment to reduce the risk of rupture and escalation.
- If a leak has occurred, blowdown will reduce the leak because of the depressurization.
- A blowdown system will route hazardous/flammable gas from the exposed segment to a safe location through a set of vent lines.

6.1.1 Utilization of blowdown

The faster depressurization is completed, the quicker hazardous gas is routed away from hazardous area. Faster reduction in pressure in segment will result in a lower leak flow should rupture occur. First in this section scenario 2 (4.4) will be simulated with an increase in size for flow orifice, allowing a flow of 150 ton/hour to form in the start of a transient release (the flow will be controlled by pressure in segment).

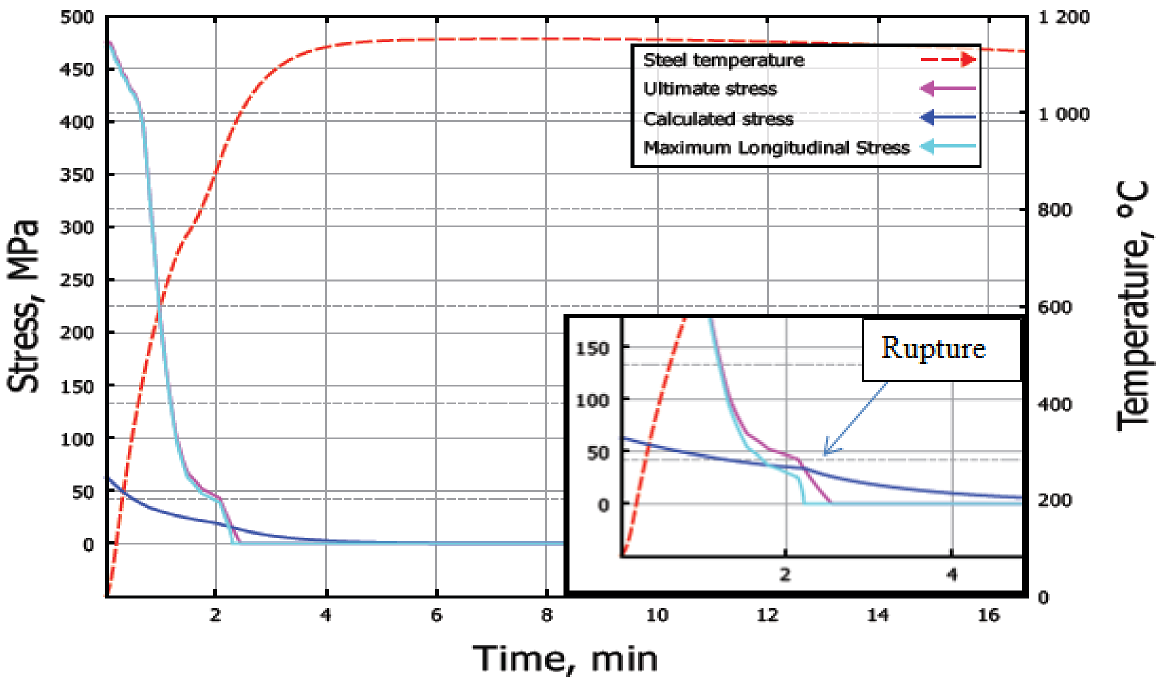


Graph 21 Stress curve increase orifice size, starting value 43 kg/s.

The comparison case is illustrated in the right corner.

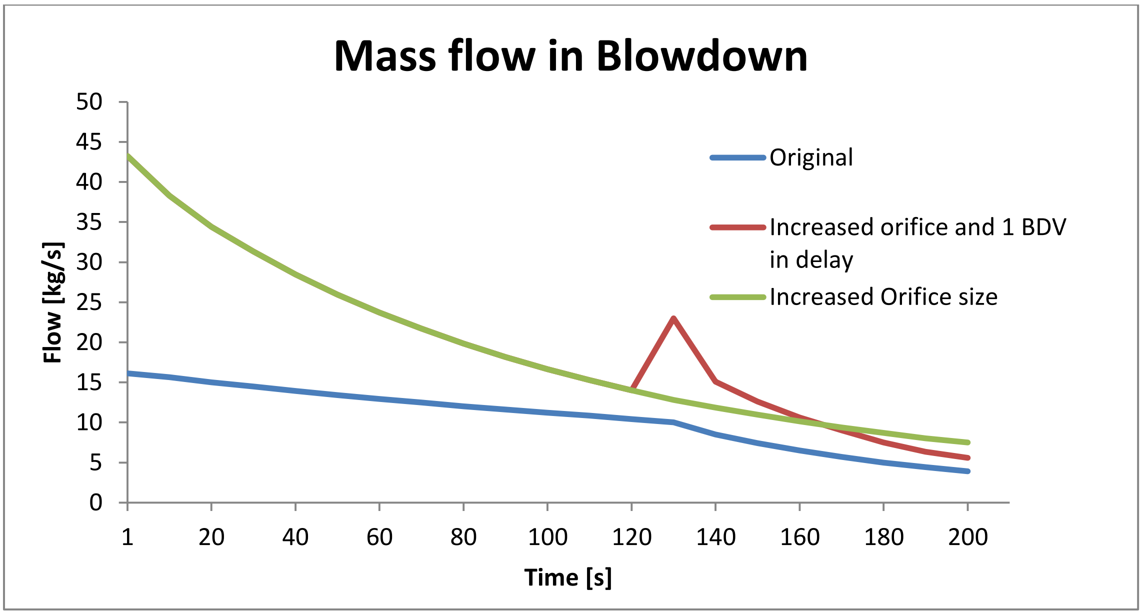
Rupture occurs after the same time as the comparison case. The difference is that the calculated stress is around half as the comparison criteria, when rupture occurs. This means that the remaining pressure inside the segment is significant lower. Remaining pressure and mass in the segment is 33.7 barg and 182 kg liquid and 1655 kg gas. Should rupture occur with additional BD capacity, then the release rate will have a peak flow in the beginning of 12.5 kg/s and decreases to 5 kg/s 1 minute after rupture occurs.

Second in this section scenario 2 will be simulated with an increased flow to the vent stack as described in the first section. There will also be a sequential blowdown sequence allowing a second orifice to open after 2 min.



Graph 22 Stress curve increase orifice size, starting value 43 kg/s and 1 BDV in delay.

As Graph 22 shows time to rupture is approximately the same (here a few second later) as the comparison criteria. The calculated stress curve is around half as the comparison criteria, this is similar as the calculated stress in the first section. The pressure inside the segment is 29.11 barg when rupture occurs, and the mass is 200 kg liquid and 1420 kg gas. The amount of liquid is higher than in the first section. Should this rupture occur, then it is assumed to have a peak value for flow at 8 kg/s and decrease to 3 kg/s after a minute.



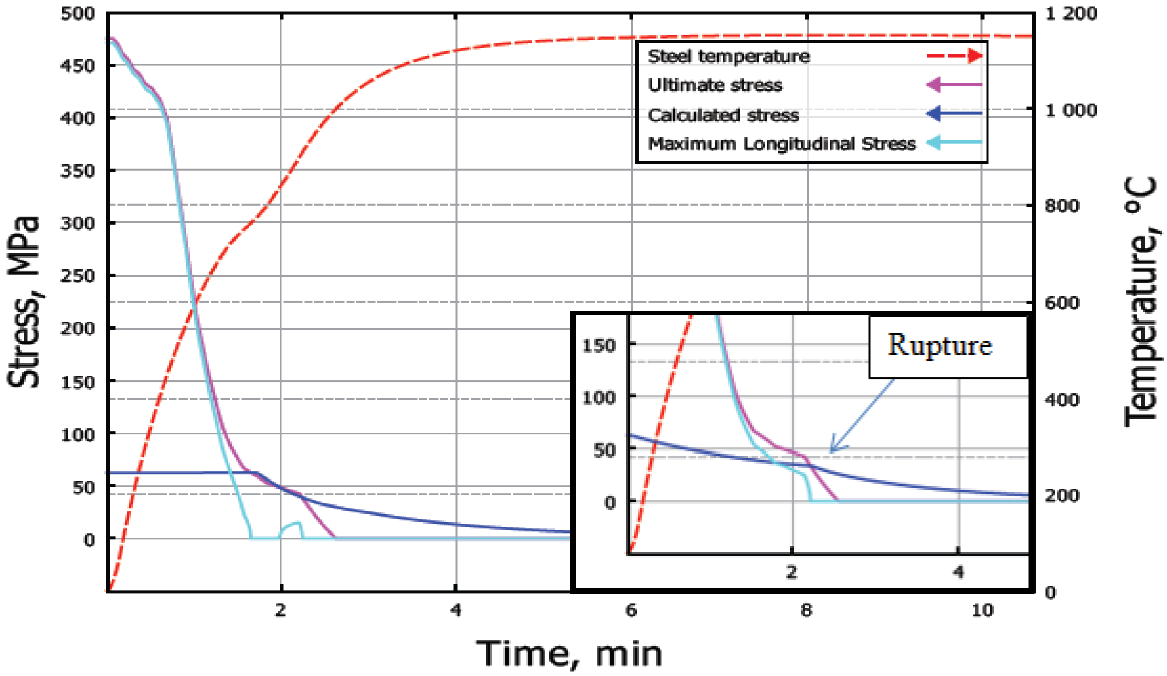
Graph 23 Flow rates for comparison.

All simulations are simulated with a starting pressure of 120 barg. The blue curve is representing the actual system as it is today (for one train), and the green and red curve have been modified to give a starting rate of about 150 tons/hour. The red curve has also one BDV with a two minutes time delay (the two curves will be identical up to the second

BDV opens). After the second BDV is opened the red curve decreases more rapidly, due to an increase in depressurization.

6.1.2 Activation time

Every simulation shown have had initiated blowdown at the same time as the leak occurs. The simulation presented in this section is simulated with a time delay for initiation of blowdown on three minutes. This to evaluate the effect and what there is to gain in an early initiated depressurization. Three minutes is being considered as an arbitrary realistic value.

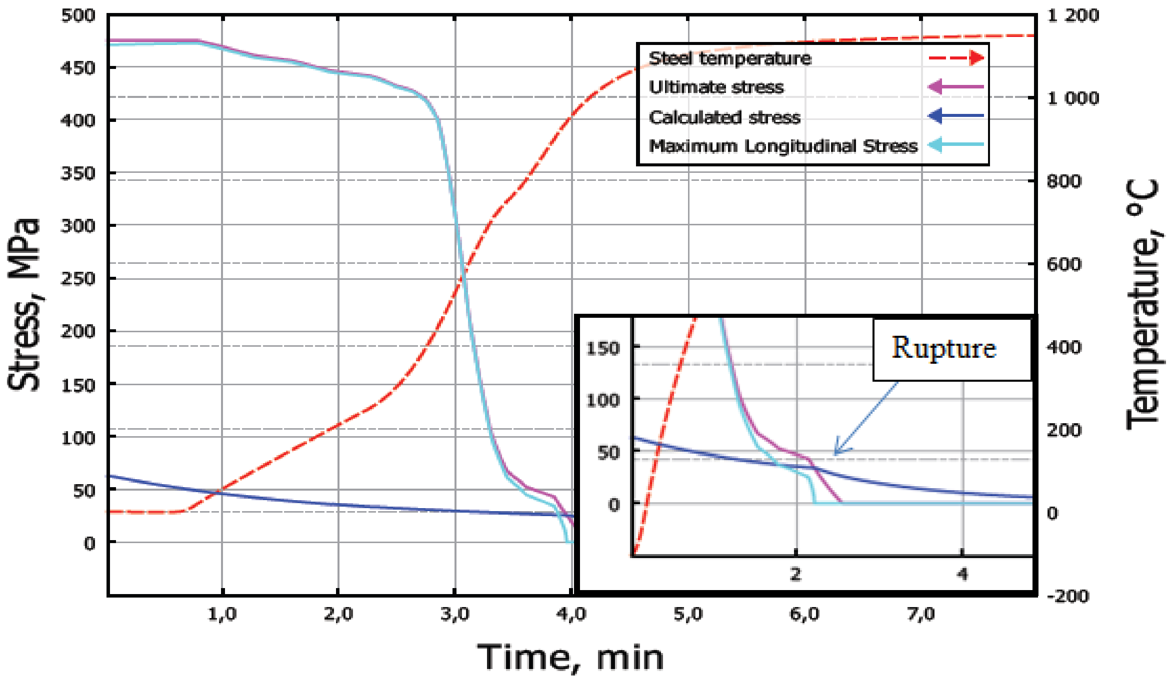


Graph 24 Stress curve, 3 min delay on initiation blowdown.

Remaining pressure and mass in the segment is 120.2 barg and 4994 kg gas (zero amount of liquid) when rupture occurs. The calculated stress curve does not decrease before rupture occurs (after 100 seconds), and blowdown is initiated over a minute later. The release flow in this rupture will have a peak value in the beginning of 50 kg/s, the rate will decrease to 20 kg/s one minute after rupture occurs. Due to an early rupture and no depressurization in the beginning, the ultimate stress curve and longitudinal stress curve will vary greatly around time to rupture. When rupture occurs, the curve for longitudinal stress will indicate no remaining strength in the pipe, and thus zero MPa.

6.2 Insulation and increased orifice size

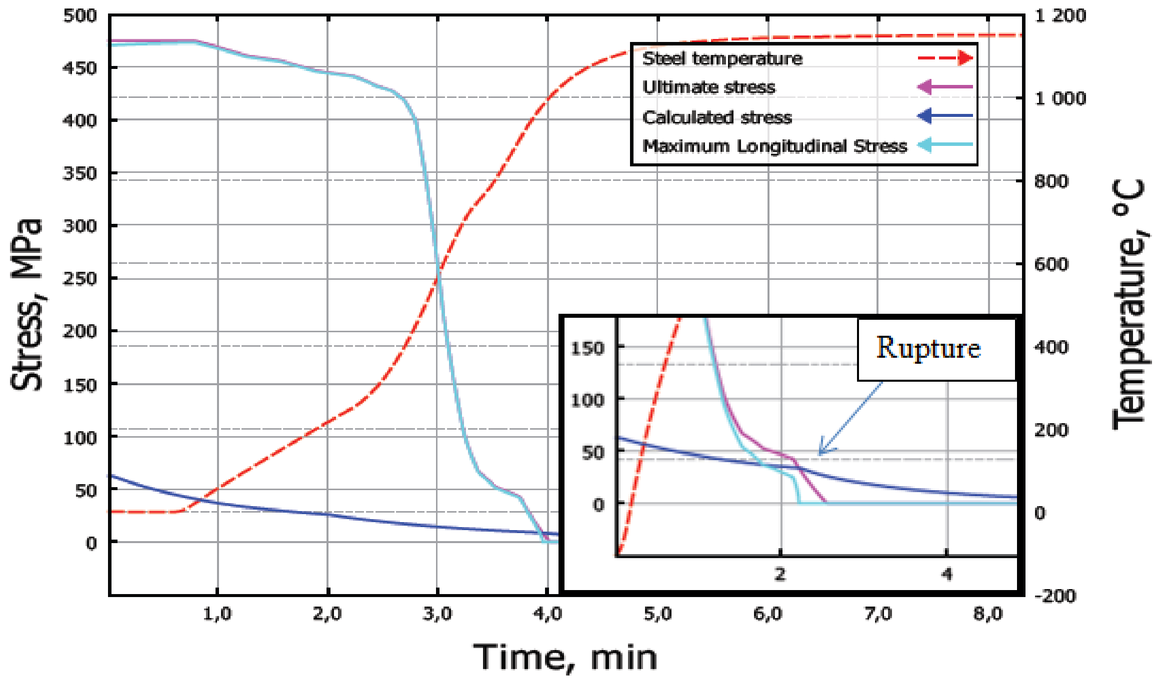
In this section the results from three simulations will be presented. In the first, exposed pipes will be equipped with 25 mm and simulated with the values for BD as the train originally have. Second, the same scenario only now simulated with an increase in orifice size. The third simulation is with 50 mm insulation, with material properties for Rockwool, and an increase in orifice size. These values are found in Vessfires.



Graph 25 Stress curve, insulation 25 mm.

Remaining pressure and mass in the segment when applying 25 mm insulation is 48.5 barg and 2341 kg gas and 71 kg liquid when rupture occurs. The calculated stress curve is similar to the criteria. However, time to rupture is 2 minutes later. The ultimate stress curve is here stabile in the beginning due to insulation “blocking” heat from affecting the pipe. The heat will penetrate the insulation after less than 3 minutes, and then will the curve decreases similar to the rest of the examples. The release flow in the rupture will have a peak value in the beginning of 20 kg/s and decrease to 9 kg/s 1 minute after rupture has occurred.

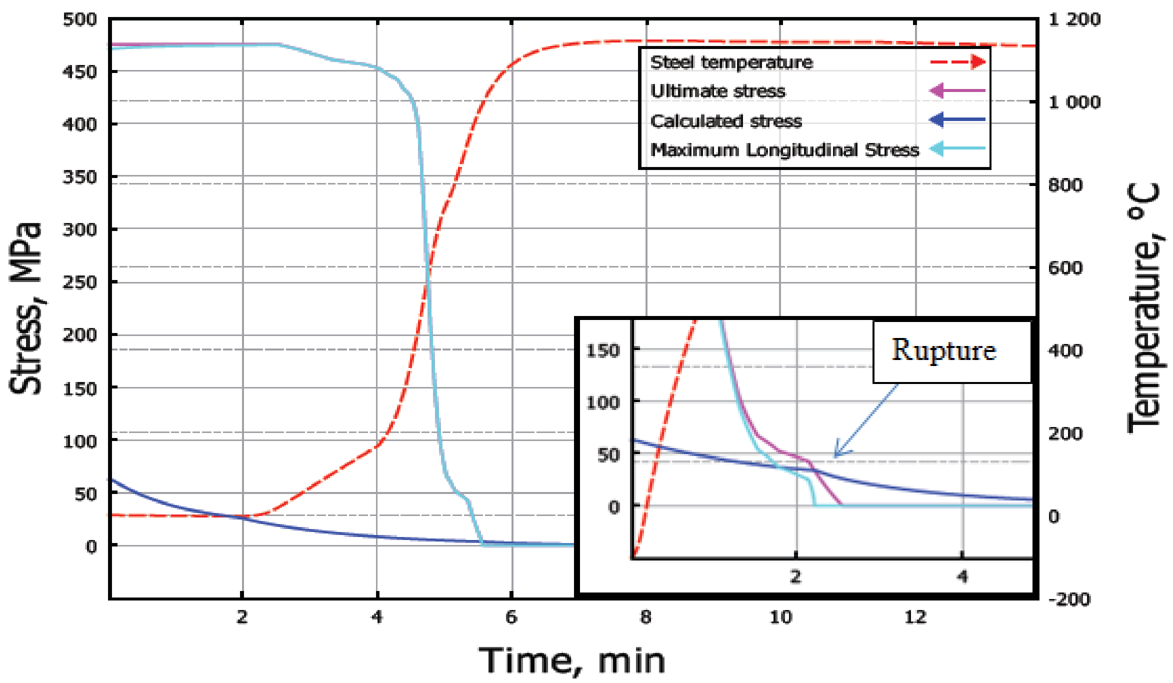
For the second simulation the orifices will behave similar as for the red curve in Graph 23 (only with peak vale of 28 kg/s in the start and 1 BDV with a 2 minutes delay bringing the mass flow back up to 28 kg/s), holding the BD flow under the vents restriction.



Graph 26 Stress curve, insulation 25 mm and increased orifice size.

Simulated time to rupture is 237 seconds, remaining pressure and mass in the segment is 16.5 barg, 182 kg liquid and 757 kg gas. The release rate through rupture when applying 25 mm insulation and an increase in BD capacity for the segment will have a peak value of 5.5kg/s and decrease to 2.5 kg/s after 1 minute.

The third simulation with 50 mm Rockwool is shown under and the same orifices area as in the previous example:

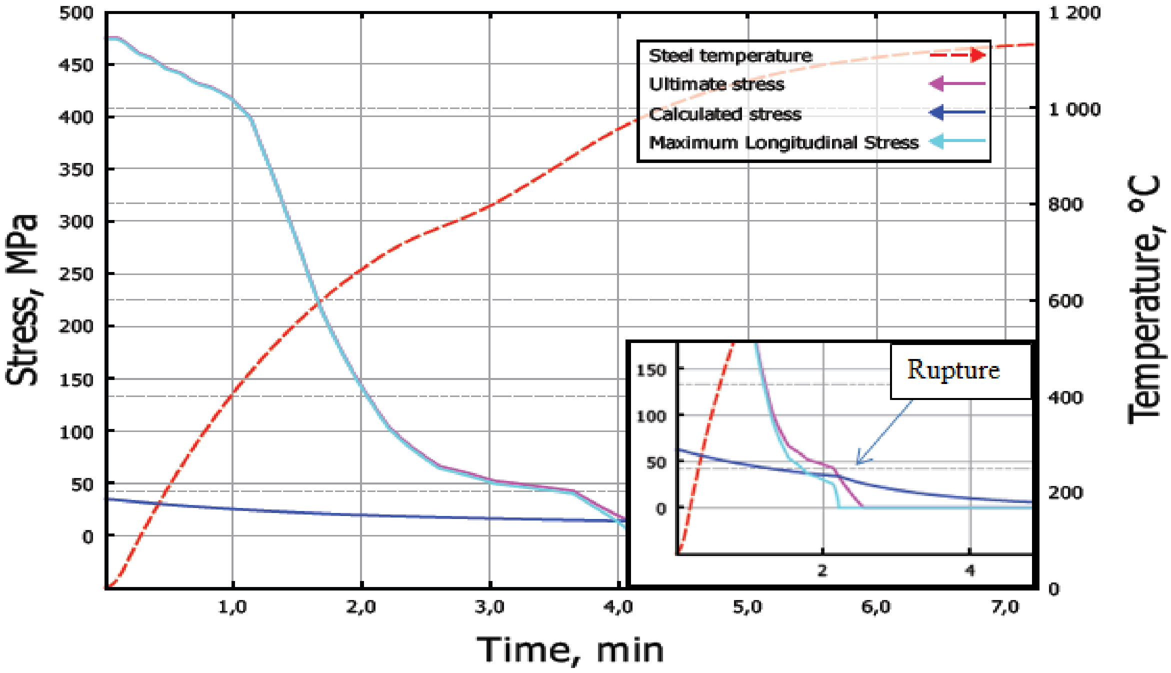


Graph 27 Stress curve, insulation 50 mm and increased orifice size.

Time to rupture is simulated to around 340 seconds, remaining pressure and mass in the segment is 6.5 barg, 154 kg liquid and 304 kg gas. The release through this rupture will have a peak value in the start of 2.5 kg/s and decrease to 1 kg/s after 1 minute.

6.3 Increased wall thickness and orifice size

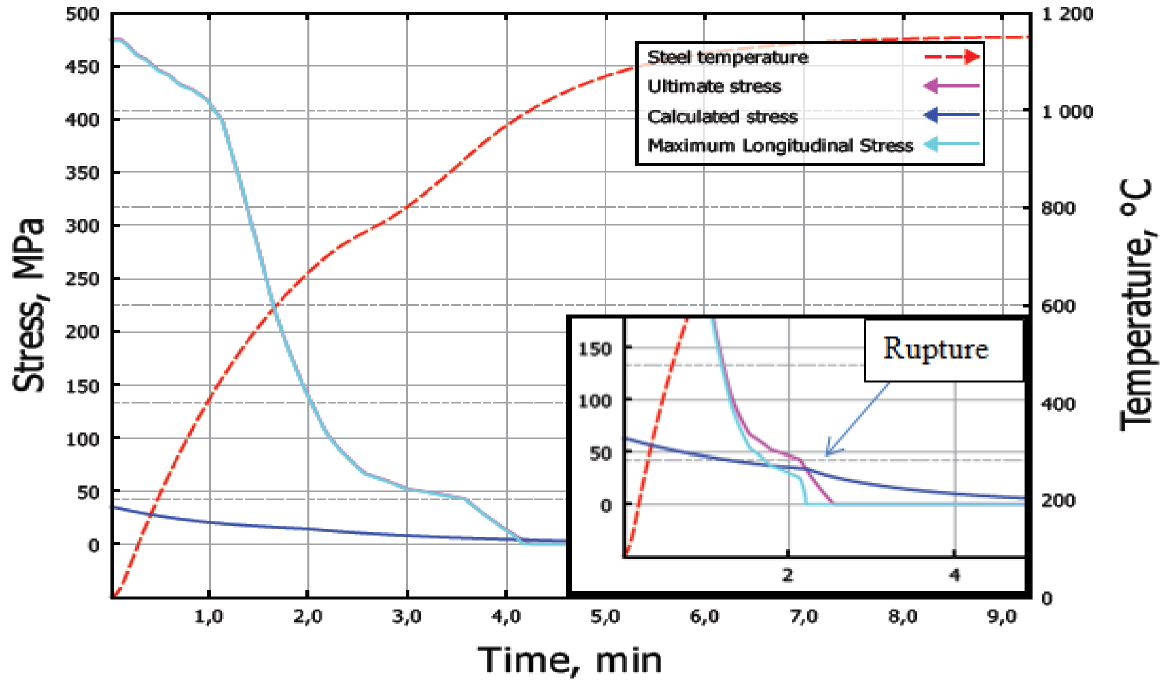
In this section, 3 different scenarios will be simulated. All with increased wall thickness, as shown in Table 4 in section 4.11(increased 100 %). The first simulation will behave as the blue curve in Graph 23, meaning original values for blowdown orifice.



Graph 28 Stress curve, increased wall thickness.

The calculated stress curve does not decrease as quickly as some of the previous examples with a higher blowdown rate. Rupture occurs after 4 minutes, the remaining pressure and mass in the segment is 47 barg and 2246 kg gas and 73 kg liquid. The curve of calculated stress starts in this case considerable lower than in other examples, due to the curve is a result of backpressure in the segment and pipe dimensions. With this measure the release flow will have a peak value of 12 kg/s in the beginning and decrease to 7.5 kg/s after a minute.

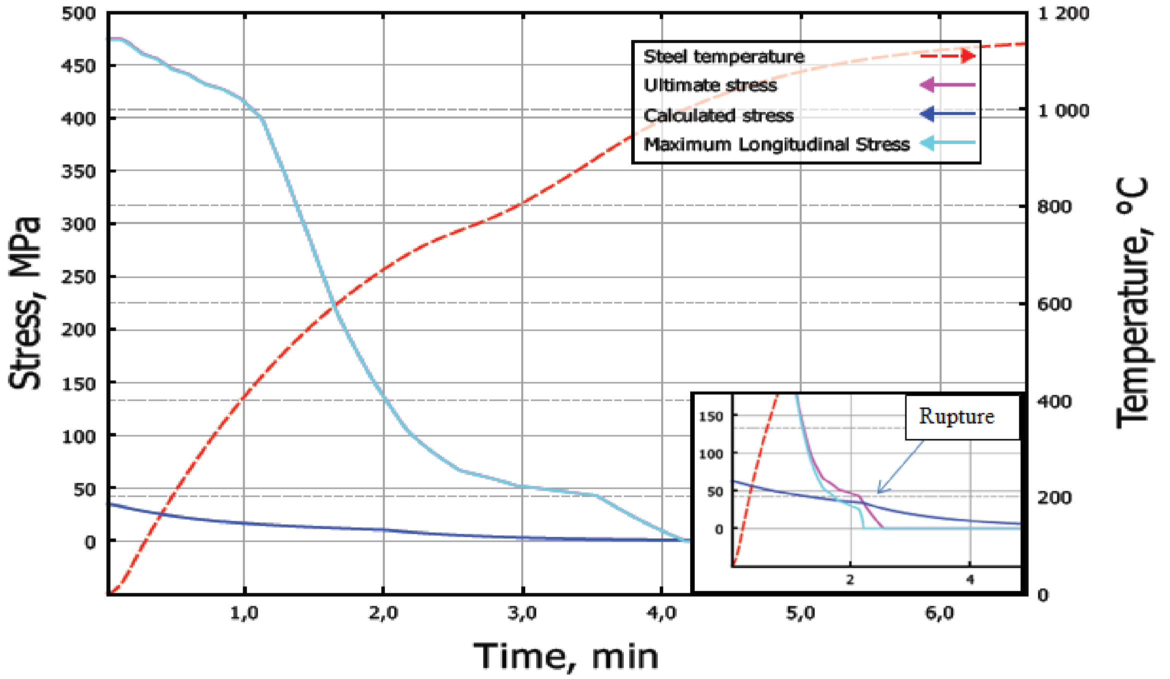
The second simulation will behave as the red curve in Graph 23, whereas the flow will start by giving 43 kg/s and 2 minutes after a new BDV will open and bring the mass flow back up to 28 kg/s.



Graph 29 Stress curve, increased wall thickness, orifice size and 1 BDV in delay.

Rupture occurs after 253 seconds, and the remaining pressure and mass in the segment is 13.7 barg and 178 kg liquid and 643 kg gas. Rupture with these safety measures will have a starting peak value for flow of 3 kg/s and decrease to 1.2 kg/s after 1 minute after rupture occurs.

The third simulation will be similar as the previous example. However, the second BDV will after two minutes open and bring the flow back up to 43 kg/s.



Graph 30 Stress curve, increased wall thickness, FO and BDV in delay (2*43kg/s).

Rupture occurs after 253 seconds. Remaining pressure and mass in the segment is 2.4 barg and 185 kg liquid and 147 kg gas. Rupture on the 2" pipe, when equipped with additional

BD capacity in the second BDV, will have a peak value for flow of 0.5 kg/s in the beginning.

In the previous sections many simulations is simulated, to make it easier to compare results. Here is a summary of the different measures evaluated in this thesis

Table 6 Risk reducing measures to evaluate for scenario 2.

Measure	Abbreviation	BD flow[6]	BD flow in 2 min delay
Reference plant	RP	58 ton/hour (16 kg/s)	-
Increased BD	A1	150 ton/hour (43 kg/s)	-
Increased flow and sequential BD	A2	150 ton/hour (43 kg/s)	100 ton/hour (28 kg/s)
Activation time	B1	58 ton/hour (16 kg/s)	(3 minutes delay)
Insulation 25 mm	C1	58 ton/hour (16 kg/s)	-
Insulation 25 mm , increased flow and sequential BD	C2	100 ton/hour (28 kg/s)	100 ton/hour (28 kg/s)
Insulation 50 mm increased flow and sequential BD	C3	100 ton/hour (28 kg/s)	100 ton/hour (28 kg/s)
Increased wall thickness.	D1	58 ton/hour (16 kg/s)	-
Increased wall thickness, increased flow and sequential BD	D2	150 ton/hour (43 kg/s)	100 ton/hour (28 kg/s)
Increased wall thickness, increased flow and sequential BD	D3	150 ton/hour (43 kg/s)	150 ton/hour (43 kg/s)

The BD flow of 58 ton/hour is the starting flow for 1 train, when depressurizes with the pressure of 120 barg.

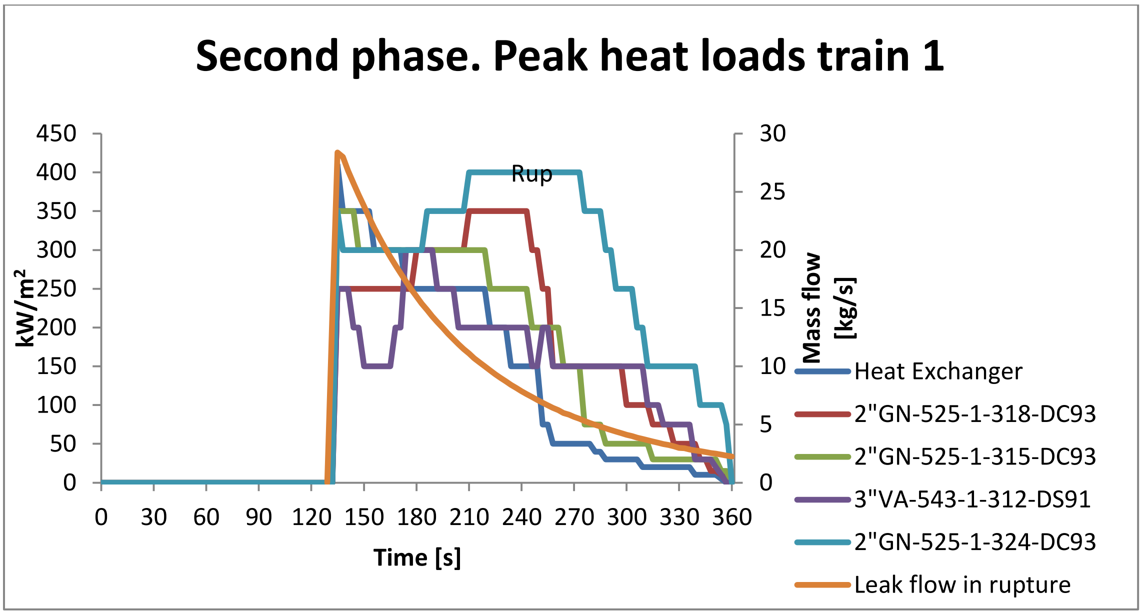
[6] This is the starting value for flow.

6.4 Discussion risk reducing measures

Ruptures are indicated to occur as the plant originally is, when pipes in the vicinity of 2 and 3 inch of diameter are exposed to a significant heat flux over 2 - 3 minutes. In part 2 and 3 of the thesis different risk reducing measures is studied. In this section their effect will be discussed.

Leaks of process materials are the process industries biggest hazard. To prevent fires and explosion, it is important to keep fuel in the plant and air out of the plant. Nitrogen is widely used to keep air out of low-pressure equipment and parts, on reference plant the vent line is flushed with nitrogen in normal operation.

Graph 31 gives peak heat fluxes and leak flow for the comparison case (scenario 2).



Graph 31 Release flow and peak heat flux for comparison.

For the exposed pipes in Graph 31, only 2"GN-525-1-324-DC93 ruptured (further mentioned as the blue curve). The blue curve and the curve for leak flow will be compared (qualitatively due to there is not conducted any simulation in KFX) to the leak flow when different risk reducing measures are used. The blue curve has a starting peak value in the range of 300 kW/m^2 and increases, when the release rate is halved. It will reach its highest value after 215 seconds of 400 kW/m^2 and be exposed to this value in 1 minute (release flow is between 15 and 5 kg/s). Rupture is indicated after 240 second, marked with "Rup" on Graph 31. A summery will be found in the end of this section comparing Graph 31 to time to rupture, when different measures are used.

The first measure is utilization[7] of blowdown. Different sizes in flow orifice (increased orifice size gives increased flow to the vent stack) are simulated and compared to scenario where a 2" pipe ruptures (scenario 2 "directed towards heat exchanger"). Multiple simulations are simulated. The first with a peak value for flow of 43 kg/s (around 150 ton/hour) in the start. The other with the same peak value in the start and an additional BDV will open after 2 min bringing the flow back up to 28 kg/s (100 ton/hour which is the restriction value for flow in the vent stack, Graph 23 shows both examples blowdown procedure). The restriction value for flow to the vent stack will be exceeded, this to

[7] Utilization: increased flow compared to the restriction value for flow.

evaluate the effect of blowdown. As the result shows, an increase in flow to the vent will depressurize the segment faster, and as the segment depressurizes the leak flow will decrease. Increased depressurization will not affect the ultimate stress curve, only heat flux and material properties like for example thermal conductivity will affect the curve. Depressurization will affect the curve for calculated stress, as the segment pressure decreases the curve will decrease, this does not occur quickly enough to prevent rupture. When comparing these two examples to the criteria in scenario 2, time to rupture is almost identical. The difference is remaining pressure and mass. For the example with a BDV in delay, this has minor effect, due to the first rupture is assumed after approximately 2 minutes. A shorter time delay would have had more effect, however minimal for time to rupture. The effect would be lower remaining pressure and mass in segment and should rupture occur, a lower release flow and duration would be expected.

Graph 23 (page 50) gives the curve for reference plant (original, blue curve), with 120 barg in the process segment. This gives a peak value in the start of 16 kg/s (around 57 ton/hour) and decreasing. From the results of the 78 barg simulation the BD rate is over 9 kg/s (around 32 tons/hour) and decreasing. From these 2 scenarios it is clearly that the utilization of depressurization is far from exploited, compared to the restriction value for flow.

Actually throughout the depressurization process around 1/3 of the capacity is used. Only in the beginning of the depressurization process is the restriction value reached with a flow of 28 kg/s (100 tons/hour). A method of utilize BD could be to have a sequential depressurization, an example of this could be:

When BD is initiated for all trains, and the restriction value is reached (or increased by 50 % as it is for some cases in this thesis, for a short time period). As the pressure decreases the flow decreases and when the flow reaches 80 tons/hour a new BDV is opened leading the flow back up to the restriction value, and this procedure is repeated until the segment is depressurized.

Another method of utilization of BD could be throttling, a given value for flow is hold throughout the depressurization. A problem with this method is that throttling needs additional equipment to keep up the BD flow, and this could cause additional risk factors.

Reference plant is equipped with a cold vent. The restriction value is set due to assumed radiation level on nearby areas and equipment should the vent ignite. An increase of 50 % utilization for a short time period could be acceptable. To answer this question a risk analysis should be conducted.

The simulation of 78 barg verifies reference plants BD procedure, if the BD flow of a single train is 32 tons/hour, the combined value should be in the vicinity of 100 tons/hour.

The second measure is activation time for initiation of blowdown. As mention earlier, time to rupture is simulated to around 2 minutes. In the majority of simulations simulated in this thesis, initiation of blowdown and the leak is initiated at the same time (time zero). This would for reference plant be unrealistic. A value for delay on activation time mentioned in the risk analysis and some earlier reports is 3 minutes for initiation of blowdown. This means almost 1 minute after the first rupture occurs, blowdown is initiated. Graph 24 shows no reduction in calculated stress until rupture occurs after less than 2 minutes. Actually the curve has a minor increase, due to a slightly increase in pressure. The rupture is the first factor which depressurizes the segment.

It is reasonable to believe that there will be a difference in manual compared to automatic BD, for reference plant blowdown is preformed manually.

When a 2” pipe ruptures with 120.2 barg, the release flow will, according to Vessfire, be 50 kg/s. Should the release be targeting train 1 or 3, escalation from a train to another would be highly possible. One train contains around 5 tons of gas, and a quick estimate of how much gas that is assumed to be released through the 2” pipe, would be in the range of 80 % (this estimate is based on leak curves in Vessfire). This statement illustrates why it is important to initiate blowdown as quickly as possible, to route flammable gas away from the fire area.

The third measure is use of insulation, combined with increased orifice size.

In the first simulation, pipes are equipped with insulation (25mm) and BD is simulated as it originally is. The result when rupture occurs is still a significant segment pressure.

When increased orifice size is used, the segment will be depressurized in a manner similar to the red curve in Graph 23, with one BDV in delay (2 peaks of 28kg/s) and equipped with 25 mm and 50 mm of Rockwool insulation. Insulation gives good results, some parts of reference plant is actually equipped with 50 mm insulation (on the low pressure part of the train). Rupture is postponed by 2 minutes with 25 mm and 3.5 minutes for 50 mm insulation. This combined with the increased depressurization effect, results in low remaining pressure in the process segment.

Insulation protects the insulated pipe, and has a low value for thermal conductivity. Low quantity of heat is able to penetrate through and expose the pipe, before the insulation reaches its saturation point and lets through large amounts of heat (in Graph 25 page 52, this occurs after less than 3 minutes, without insulation heat penetration occurs instantly).

Although insulation gives promising results in how to efficiently protect pipes and pipelines against ruptures due to heat exposure, there are some negative sides. On reference plant there is as mentioned some insulation, the insulation is held on place with a thin steel mantle. A problem with insulation and this method is the weight, increased reflected radiation (because of the steel) and corrosion [23] and it could be difficult and expensive to maintain.

When some organic compounds come into contact with hot insulation materials, they can degrade, resulting in a decrease in auto-ignition temperature in the range of 100 to 200 degrees Celsius [22]. In fact many fires have started this way. Most of them have been small. However, some have been serious. This is mentioned in general, and it’s relevance to reference plant is assumed to be low.

Another problem can be use of insolation to compensate for a low depressurization flow to vent stack. This could lead to a higher release flow, should rupture occur. More hazardous fluid could escape through the potential leak and the duration of the jet could be longer. In S-001 it is mentioned that passive fire protection (PFP) is only to be considered as a supplement to blowdown.

The fourth measure is increased wall thickness as the blowdown system originally is, and increased wall thickness and orifice size (in all cases wall thickness is increased by 100%). Increased wall thickness on smaller pipes could be a cheaper solution (for new process plants) than insulation and easier to maintain.

Graph 28 (page 54) have a lower starting value for calculated stress, how the curve will further decrease depends on depressurization. All 3 simulations conducted under this measure have the same time to rupture, which is around 4 minutes. For comparison, time to rupture with 25 mm insulation is right under 4 minutes. This means an increase in 100% wall thickness for the steel properties used in the thesis, 25 mm insulation (Rockwool) gives approximately the same results for time to rupture for a 2” pipe.

Reference plant is equipped with some pressure safety valves (PSV). Their effect is not evaluated in this thesis due to the focus on escalation and effect of blowdown.

The fifth measure is inherently safer design; Reference plant is a simple process plant and its function is mainly gas conditioning. Inherent safer design is typically know by 4 factors [22]:

Minimization: Use as little hazardous material as possible, so should any leak occur, it will have very little to say.

Substitution: Use as safe materials as possible.

Moderation: If the two first factors aren’t possible, and the plant have to store or handle large amount of hazardous material, it should be stored and handled in its least hazardous form.

Process layout: For example in form of distance between hazardous objects, use of safety devices/equipment or material type/properties used for pipes and vessels.

For reference plant and its function the three first points will be difficult to do anything with. However, in the process layout there could be something to gain. Scenario 4, concerning an ignited jet fire, formed on train 2 targeting train 3. Due to the large distance and small volumes in segment the incoming radiation is insignificant and the duration is short. The result recorded no ruptures, this when the initial leak rate is 2 kg/s. An increase in leak flow could result in a higher value for radiation (because of the increase in size). Should the jet embrace parts of train 3, an increase in convective heat would be assumed. However, the duration will decrease. It should also be mention that scenario 1 has a starting release flow of 7.5 kg/s directed the same way, and the length is approximately twice as large (around 25 meters). The distance between train 2 and 3 is around 20 meters.

If large distances aren’t possible between hazardous objects, then “protection” plates of a type of metal with very high thermal conductivity may be considered. And further irradiate out large quantity of incoming heat from 2 sides (low emissivity). These plates will need maintenance and are assumed to lose its thermal properties when targeted by a jet fire (example, the white area could turn black, giving an increase in emissivity).

Risk reducing measures summary:

Table 7 Risk reducing measures summary.

Measure	Time to rupture [s]	Starting release flow [kg/s]	Pressure when rupture occur	Flow after 1 min [kg/s]
RP	133	28	64.26	15
A1	133	12.5	33.7	5
A2	133	8	29.11	3
B1	100	50	120.2	20
C1	240	20	48.5	9
C2	237	5.5	16.5	2.5
C3	340	2.5	6.5	1
D1	240	12	47	7.5
D2	253	3	13.7	1.2
D3	253	0.5	2.4	-

The heat load for the actual pipe (criteria 2”pipe) will be highest when the release flow is in the range of 15 to 5 kg/s. Before rupture occurs the pipe is exposed to a heat flux in the vicinity of 300 to 400 kW/m^2 for almost two minutes. From this reasoning, Table 7 and from what that is already mentioned in chapter 6, it could be likely to believe that the following scenarios will not record any further escalation, with the assumption used in this thesis:

- A2, C2, C3, D2 and D3.

For the rest of the simulations it will be impossible to predict any outcome without simulate the different cases in KFX.

An increase in orifice area (A2) is assumed to be sufficient enough as measure to prevent any further escalation for this given scenario. As well as when insulation and increased wall thickness is used, supplemented by an increase in orifice area (allowing a higher flow to the vent stack).

Because reference plant is an all existing plant, changes can be expensive. Additional changes on the blowdown system could result in a new vent stack, change in pipe diameter will result in new pipes. A recommendation for reference plant may therefore be to equip smaller pipes with 50mm insulation and focus on quick activation time for initiation of blowdown. Even though an overall recommendation for new process plants would be focus on quick activation time for blowdown, and sequential depressurization for better utilization of blowdown capacity as well as an increase in shell diameter for smaller pipes.

7 Discussion

This chapter will discuss some additional findings and previous conducted related/similar studies.

7.1 NORSOK Standard S-001 and API criteria

In NORSOK Standard S-001 [1] there is presented a method of dimension the depressurization capacity by using standardized values for global heat load. Peak loads are typically used in escalation studies. In this section this method will be compared to simulations conducted in this thesis. The comparison scenario will be scenario 6 (initial leak flow 7.5 kg/s) and scenario 2 (initial leak flow 1.96 kg/s).

Table 8 Standardized heat loads.

	Jet fire		Pool fire
	For leak rates m > 2 kg/s	For leak rates m > 0.1 kg/s *)	
Local peak heat load	350 kW/m^2	250 kW/m^2	150 kW/m^2
Global average heat load	100 kW/m^2	0 kW/m^2	100 kW/m^2

A common interpretation is that the whole geometry, according to S-001, will be affected by a global heat load, when dimensioning the depressurization capacity of the blowdown system. To set this in perspective a reality check is conducted, let's say a train is 80 meters long and consist only of a 24" pipeline and a separator which will give an area of about 165 m^2. The formula used is shown under:

$$area = 2\pi r * h \qquad (11)$$

Whereas r is radius and h is the length of the pipe (the top and bottom area is not taken into consideration), for the separator there has been chosen values r like 1 meter and h like 2 meters (just to keep it simple). The actual area for a process train in reference plant is assumed larger.

The next step is to evaluate the actual reality check:

Outer area*global heat load < combustibility * flow rate (the total effect of the flame) [20].

On the left side is the effect of the heat flux exposure given by the interpretation to the system by using standardized values, on the right side is the total effect of the flame. The total effect of the flame should be larger than the exposure given to the geometry.

Assume a combustibility of 50 MJ/kg, and a leak rate of 7.5 kg/s (which in this thesis is time dependent). In 1 train there is approximately 5 tons of gas.

$$165m^2 * 100\frac{kW}{m^2} < 50 * 10^3\frac{kJ}{kg} * 7{,}5\frac{kg}{s}$$

$$16500\ kW < 375000\ kW$$

For a leak rate of 7.5 kg/s 4.4 % of the effect of the fire goes into the segment (16500 kW are 4.4 % of 375 000 kW). The jet fire will be able to last for around 11 minutes. This is a simple method to get an idea if the global heat load is representative for the size of geometry used.

The following graphs (Graph 2 page 30, Graph 4 page 31, Graph 8 page 33) indicates that the value of 100 kW/m^2 could be representative for some pipes. However, for Graph 14 (page 39) it will be too small. The global load is as the peak load dependent on the geometry (size) and direction of the jet fire, especially when the leak decreases rapidly in the beginning, due to the small process volumes and relative high release flow.

In some of the conducted simulation (especially scenario 3 and partly 2, with initial leak flow under 2 kg/s) other objects could work as flame stabilizers. This could result in a relatively high peak heat load exposing smaller pipes over a longer period. The peak heat load will be in the range of 350 to 250 kW/m^2 in the start of the leak. A large quantity of nearby pipes will be effected with a global heat load in the range of 80 – 180 kW/m^2 over a few minuts. If the release flow were constant, it is reasoneble to belive that the global heat load would have stayed in that range, due to the geometry.

The fact that around 1/5 of reference plant is affected by the global heat load in scenario 3 will possibly not have to much to say for the pressure developmet inside the segment. It shall be mentioned that no scenario or phase in this thesis will affect the whole train. For a smaller plant the contribution could be in the range of concern.

In Scandpower’s report [10] there is a foot note stating that the values for heat flux given in Table 8 are meant for an object close to the leak source. This is a statement that in some degree could fit better. However, it is not mentioned in S-001 [1]. The geometry could play a huge part in how the jet will develop.

In this thesis there have been conducted simulations by the method described in this section, where standard values for global and peak loads (a peak load will affect a small area of every part of the train) are used to expose a whole train. Values for a leak larger than 2 kg/s are chosen, and the geometry and properties for reference plant is used (120 barg). The result was that every pipe in the process system ruptured, 2” pipes ruptured after 2 minutes, 3” pipe after around 3 minutes and for 24” less than 15 minutes.

Time to rupture when standardized values is used, is similar to time to rupture with heat flux values simulated in this thesis. This was expected due to the peak heat load for the 2” pipe in scenario 2, which this chapter is compared to has a peak value of approximately 350 kW/m^2 for the first 650 seconds (that leak was under 2 kg/s), which means that the value used should actually be 250 kW/m^2. After conducting these changes a new simulation is simulated, rupture occurred after exactly 3 minutes for the same 2” pipe. This is 1 minute after the rupture in scenario 2.

Some other values for peak heat flux are simulated for comparison. When a value of 200 kW/m^2 is used for peak heat load, rupture is indicated after 3.5 min for 2” pipes and 7 min for 3” pipes. When 300 kW/m^2 is used rupture is indicated after 2.5 min for 2” pipe and 4.5 min for 3” pipes.

Through the reasoning in this section, standardized values for heat loads can fit for some cases, but in reality it is not that simple. The geometry could play an important part in how to define a fire scenario. If this were conservative then it had been understandable, however in the last example the 2” pipe ruptured 1 minute after the scenario 2 in this thesis. 1 minute is an increase in time of 50 %. Scenario 2 will far from be representable for all cases. However, the result from the simulated scenario provides a basis for discussion.

From Table 8, the peak heat load will be dependent on rate of turbulence (typically as a result from objects and other obstacles that are in the jet fire way) and if there is contact (radiation and or convective heat transfer). The value for global heat load will be more dependent in the size of the jet fire compared to the size of the geometry, and thus the release flow.

Design criteria for emergency depressurization for reference plant is after API to reduce the pressure to a maximum of 6.9 barg in 15 minutes, due to 6.9 barg is lower than half the design pressure. From simulation results, rupture occurs on smaller exposed pipes after few minutes. This means that the pressure inside the segment could still be of considerable value. However, reference plant depressurization policy states that the actual depressurization time shall ensure non-escalation in the event of a jet fire. In this thesis escalation has occurred for some of the chosen scenarios. Independent on how the scenario occurs or develop, should pipes in the range of 2 and 3 inch of diameter be exposed to heat flux over 300 kW/m^2 for a couple of minutes with the steel type and property used in this thesis could rupture occur. This means, rupture takes place before 6.9 barg is reached.

7.2 The use of simulation tools.

Kameleon KFX and Vessfire are used in this thesis. In this section their limitations will be discussed against the method used in this study. However, it must first be mentioned that these complex simulation tools have many impressive sides, and even though some limitations is found, it’s by good reason that the industrial marked in Norway prefer and recommend these tools.

A question that is often asked when results from simulation is presented is whether they are realistic or not, and if the input is representative for the actual case. The purpose in this thesis is in many ways not to take any short cuts, and to see if the simulations tools used allows this, inside reasonable time and what requirements this would require by the user.

KFX has a grid system consisting of control volumes, where different control volumes can vary in size. Close to the leak and in the leaks direction the control volumes are typically small, and as longer away from the leak point the larger the volumes gets. The area of interest is often in the beginning of the simulation as the fire develops.

The maximum length of stable (and time accurate) time steps depends on the ratio between length of the control volume and the local velocity. This means that a high grid resolution (small volumes) enforces smaller time steps and therefore increased simulation time.

The size of control volumes around the leak origin is chosen on the basis of leak flow and velocity (and can be read as an equivalent diameter). Typically low release flow results in smaller control volumes around the leak, and for large release flow with a high velocity allow larger control volumes. A control volume cannot change size.

In this thesis KFX has been simulated with a transient leak flow and in some cases the leak flow will change from 60 kg/s to 2 kg/s in a few seconds. This will for the 60 kg/s rate give an equivalent diameter on 0.64 m, and for the leak flow 2 kg/s give an equivalent diameter on 0.11 m. This requires some knowledge, due to the user now has to adopt a grid for each leak origin and the difference in recommended size for control volumes are large.

To give an example, scenario 2 first and second phase; the leak in the first phase have a starting flow of 2 kg/s directed south, this initial leak results in a rupture on a 2” pipe. The new release flow has a peak flow of 28 kg/s directed east and is decreasing quickly. Here there are two different leaks in the range of 3 meters of each other and the leak flow of 28 kg/s is only representative for a few seconds. KFX adopts the grid around one leak origin automatically. Further the user has to adopt the grid around the other leak as best as possible and for the highest leak choose a lower value for equivalent diameter, with the same value for flow. This could result in a lower value of impulse for the release (to see any changes in the jets behaviour the change of impulse must be of a significant value). Further the user has to decrease the value for allowed time step, maybe as much as 10 to 15 times. This is tried and achieved in this thesis and the result was an increase in simulation time.

In this thesis a single event/leak is simulated in one simulation. Meaning interaction between multiple jet fires and or leaks is not simulated due to long simulation time. The effect this simplification would have on the result is difficult to predict. However, it is assumed to have little effect in this thesis, due to the initial leak starts with a flow of 2 kg/s and is quickly decreasing. When rupture occur the initial leak decreases to a value in the range of 0.4 - 0.7 kg/s due to the quick depressurization of the rupture. The contribution of the initial leak will thus be small. In some cases simulated the initial leak actually extinguished, due to the temperature in the control volumes close to the leak was too low.

Vessfire is a simulation system for calculation of integrity of process components exposed or unexposed to fire. The program is user friendly, large amount of pre-defined data is stored as insulation material properties, different gas properties and some material types. The simulation time is only a couple of hours. Vessfire even defines the amount and place of control volumes used in a simulation, whereas a pipe or vessel shell is set with a minimum of 2 control volumes.

The simulation boundary in Vessfire is the segment up to the flow orifice, back pressure (pressure in the vent line) will be hold constant to a pre-define value set by the user (typically 1 atm).

In Vessfire the peak heat load is set automatically on the right corner and exposes a small part of the pipe (on vessels the exposed area is 1%). For one pipe the user can define one global and one peak heat load. The affected area by the heat load will be the same throughout the simulation, the strength can vary with time, however not location. Would this be representable? In Appendix B there are some figures with heat imprints simulated in KFX. For some pipes its shows that the affected area by the peak heat load changes position as the release flow decreases. In some scenarios maybe as much as 1.5 meters. An example is given under where it shows one pipe and two hot spots.

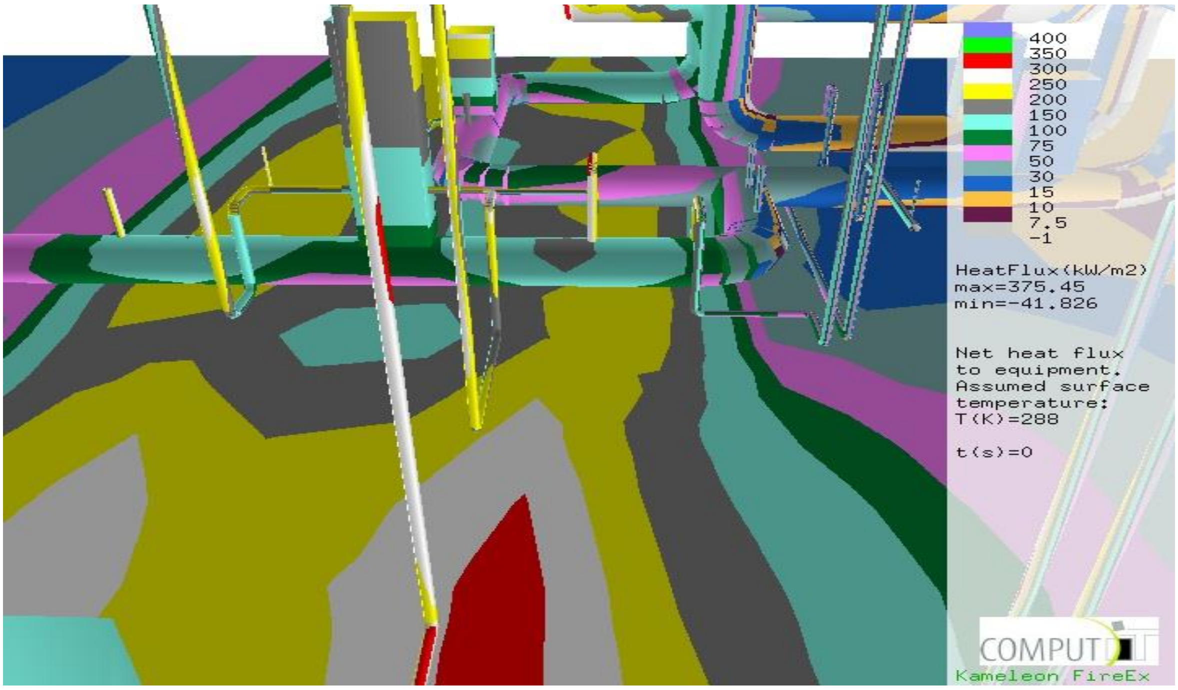


Figure 25 Illustration hotspot.

The phenomena where hot spots change location, seems to be dependent on geometry. When a jet is targeting many or large objects the hot spot will typically increase or decrease in the same area. However, if the jet is less affected by geometry the hot spot could move over a larger area as the jet increases or decreases in size.

In section 7.3 under “increase in turbulence” it will be described how larger objects could result in an increase in turbulence.

For this thesis and for blowdown studies in general a simulation tool that could simulate the whole process site and how sequential blowdown interacts with the flow and backpressure in the vent lines could be more accurate. The simulation process in this thesis was a bit cumbersome.

7.3 Simulation with 78 barg in segment and simulation phenomenon

In this section the differences between having 120 and 78 barg in process segment will be discussed, as well as some simulation phenomenon.

In this thesis the majority of simulations are simulated with 120 barg pressure. If 78 barg were chosen instead of 120 barg, then it would have been more custom to reference plants BD philosophy. The down-side with using 78 barg, is that the accident is assumed to start before the depressurization process. As mentioned under system description, a train will first be sectionalized when the pressure is 78 barg (BD is assumed initiated earlier). It is difficult to simulate a similar effect as the pressure reduction from 120 to 78 barg in Vessfire, and to estimate the time of the whole process as it is conducted manually. An estimate could be 90 seconds. Should the simulation start at 78 barg, then 90 seconds of exposure from a jet fire would be lost, and the focus for this thesis is effect of blowdown and escalation. 120 barg as set pressure seemed therefore to be most accurate for the given purpose.

Rupture occurs after approximately the same time, the difference in remaining pressure is only around 12 barg higher for the scenario with 120 barg, which will depressurize quicker in the beginning due to higher initial pressure.

Low temperature:

Low temperature could have positive effects, for instant the cooling effect. However, there could also be negative sides. The metal can become brittle due to reduction in temperature and rupture earlier than expected [22].

The property for thermal conductivity for liquid is higher than for gases. Meaning liquid will transport more heat away from adjacent metal like pipes or vessels. This can result in cold spots on the lower part of the segment. When a pipeline gets heated up to a given temperature it will expand, causing longitude stress to form on the pipeline. When it is being cooled down the pipe gets more vulnerable against external actions like impacts etc. In section 2.4 the design criteria for reference plant is given, and it states that the minimum design temperature upstream HIPPS is – 29℃ and downstream HIPPS is -46℃. Steel temperature in the vent line is after simulation results to be expected in the range of -50 to -90℃ for around four minutes (in the beginning of BD). As mentioned the gas temperature is expected to be in the range of -80 to -100℃ for two to three minutes, and under -40℃ for five to six minutes. This will depend on the rate of depressurization (this result is from simulation as the plant original is). An increase in depressurization gave a higher peak value (closer to -100℃), however over a shorter time period.

Leak flow:

Rupture increases the depressurization process, due to the amount of mass that escapes through the rupture. Due to the link between release flow and pressure, the leak flow is time dependent. Some factors like for instant segment volume and pressure, could make a difference in how fast the leak would decrease. The release flow when rupture will almost immediately reach its peak value, an example is given in Table 9 under (BD is initiated):

Scenario 3, first phase (rupture in a 3” pipe):

Table 9 Time dependence in leak flow.

Time [s]	Release flow [kg/s]	Pressure [barg]
191.4	0	50.68
192	41.1	49
192.5	60	47.9
193	58.14	47.2
194	56.37	45.9
195	54.68	44.6
196	53	43.35
210	35.3	29.2

Table 9 gives release flow at a given time, and the flow will after 20 seconds be almost halved. Table 9 is to illustrate the dependence between leak flow and pressure/ pressure drop in the segment.

Increase in turbulence:

In some of the conducted simulations the jet is directed into other objects as for example a 24” pipeline. In multiple simulated scenarios the recorded heat flux looks to increases after passing these objects. The 2” rupture in third phase is a product of this effect. The piping of interest is targeted with white arrows in Figure 26 and the jets direction is illustrated by a yellow arrow.

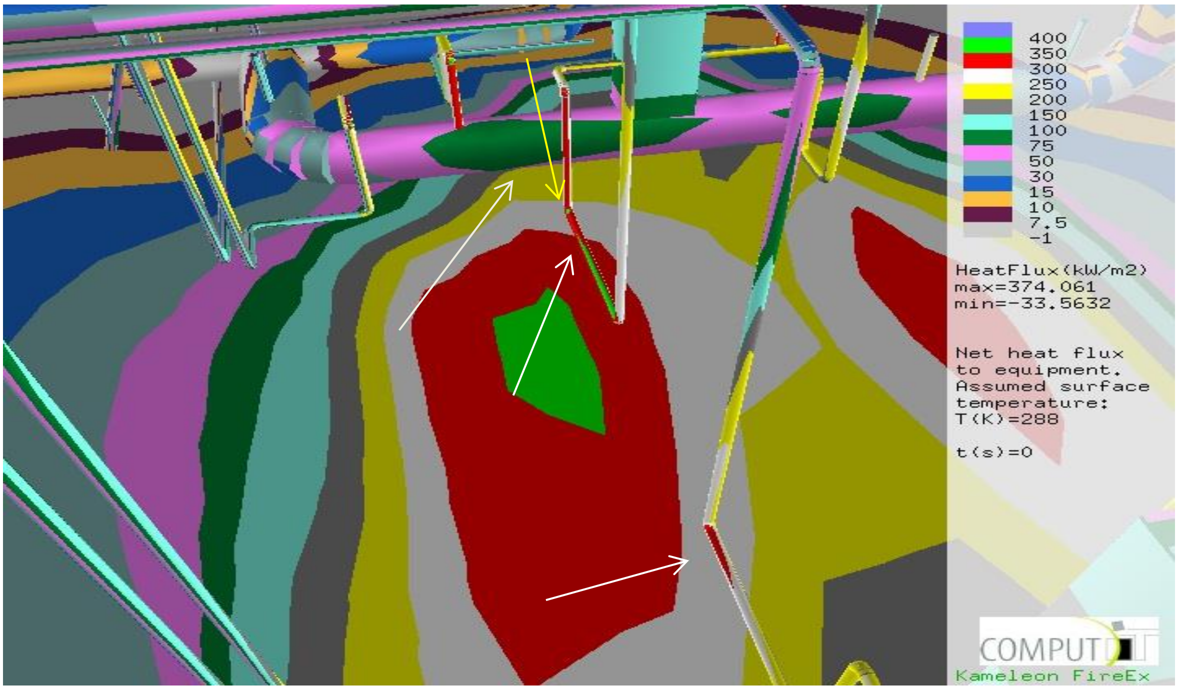


Figure 26 Illustration of increased turbulence when the jet passes through objects.

The reason for this phenomenon could be an increase in turbulence, when the flow passes the object (which in this case is a 24” pipeline), forcing the gas to accelerate (a higher amount of air will be mixed into the jet, resulting in an increase in combustion). Leading to an increase in thermal combustion, as well as the amount of convective heat transfer increases (due to loss of impulse and a decrease in flow velocity).

Object as flame stabilizer:

The values for both peak and global heat fluxes will in some cases be dependent on geometry as well as the release flow in the leak. Figure 27 shows the most obvious example on how objects can work as flame stabilizers.

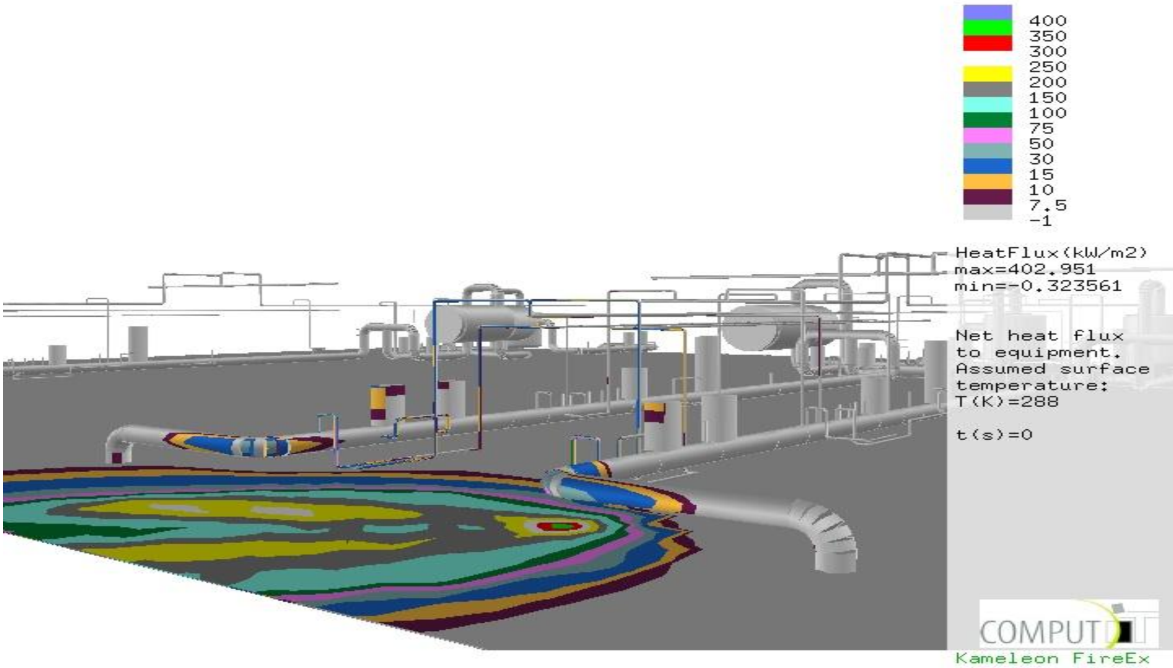


Figure 27 Illustration, objects as flame stabilizers.

Even though the release flow is decreasing, the values for heat fluxes as well as change in position of hot spots, will be held approximately constant over a longer period, when targeted into larger objects. In Figure 27 the ground will crush the jet (the ground works as a flame stabilizer) and the values for heat flux affected nearby pipes will be stabile almost throughout the simulation. This phenomenon has been present in other scenarios where the initial leak has been directed into a 24” pipeline.

7.4 Previous conducted studies

This section will mention and compare previous similar studies to the result in this thesis. It was not easy to find similar studies where transient leak flow as well as exposure by a jet fire is used. Actually one of the studies found was published January 2013 [25] (6 months after this thesis was started, and they describe the same difficulties with finding similar reports).

In 2004 Scandpower conducted a study called “Guidelines for the Protection of pressurised System Exposed to Fire” [10]. This study has been mentioned previously in this thesis, and will thus be mention briefly in this section. The report gives general guidelines on fire protection measures as well as standardized values for exposure by fire, these values is found through numerous simulations. The guidelines further describe how both global and peak values for heat flux can vary with transient variations in a fire (especially jet fires). The result in this thesis can agree to that statement when applied to global heat loads. However, for peak heat loads did neither the strength of the flux or the area affected by the peak load (highest recorded value for heat flux) vary significantly with size of the jet fire. And this statement is from this thesis point of view, valid for scenarios where the jet fire is placed a few meters from objects (with the given properties and direction). The guidelines [10] can be interpreted; Exposure by a jet fire is controlled by leak flow.

Results in this thesis indicate that this effect is primarily due to geometric differences (this applies when the jet fire is affected by objects). Geometry could play a significant part in how a fire scenario will develop, especially for peak heat loads. This statement is supported by the article “A risk-based decision making approach to determine fireproofing requirements against jet fire” [25]. The basic objective for this article is to introduce a new method for determination of necessity for fire proofing of structural supports against jet fires. The approach in this article is similar to the one used in this thesis (use of transient variation in the jet and multiple scenarios evaluated, before selecting one “worst case scenario”).

The method presented in the article is described as a risk-based methodology. The process method should be capable of integrating the effect of main parameters identified theoretically and empirically as the effective elements in fireproofing.

The article states that few studies are carried out addressing the effect of jet fires despite its significant importance, and concludes with the recommendation to focus on use of high resistant structures, shorter length on piping and process layout among others. This is similar to the result in this thesis. However, in defining the method developed in the article an assumption is made, stating empirically, it is known that higher operating pressure leads to more destructive jet fires. This statement/assumption will form the basis in the method. The result in this thesis indicates that the assumption used in the article could narrow the application for the method developed. Even for jet fires developed on high pressure equipment, will process layout and direction of the jet fire, be two central parameters in how the jet will evolve and expose other close by objects. Due to duration of a jet fire is controlled by segment volume (size) and rate of depressurization. In some scenarios could the process segment depressurize quicker, due to a high release flow. This phenomenon is shown through the result in scenario 3 (escalation is assumed for this scenario if lower pressure and different direction is applied).

8 Conclusion

The thesis approach of evaluation on escalation and effect of blowdown, as well as the effect from risk reducing measures such as insulation, increased blowdown rate and increased wall thickness, through eight pre-defined scenarios. Where jet fire and gas dispersion are studied by using transient curves for leak flow in two simulation tools, the first Kameleon KFX to simulate jet fire and/or gas dispersion, second Vessfire for calculation of the effect/ integrity of process equipment, gave the following results.

Escalation is likely to occur when pressurized pipes up to 3 inch of diameter is exposed to heat flux over 300 kW/m^2 for more than two minutes. So it is important to look further into this.

The blowdown system, with its restriction value for flow, will not alone prevent escalation to occur, when smaller pipes are exposed as described above. Even with an increase in 50 % flow and further utilization of a BDV in delay, escalation is likely to occur within the same process train. With an increase and sequential depressurization procedure, escalation from a process train to another is proven to be less likely. However activation time for initiation of blowdown will be an essential factor.

Results in this thesis demonstrates poor utilization of blowdown, the restriction value is only met in the beginning. A recommendation must therefore be that a sequential blowdown philosophy is used with a supplement of increased wall thickness for smaller pipes, typically up to 4 inch of diameter. However, it could be difficult and expensive to equip reference plant with these changes. The results indicate weakness in the safety system present to day and further use of insulation should thus be considered. Utilization of depressurization is essential to prevent any further escalation, should a leak occur.

Even though both Vessfire and Kameleon KFX have a well-adapted and “easy to use” user interface to solve escalation related issues, still some assumptions must be made to conduct these types of simulations. The work process of using multiple simulation tools to evaluated escalation is cumbersome, and there would be preferable to have a simulation model to solve the whole scenario. However a large step in the right direction would be to adapt KFXs grid model to simulate multiple releases, and develop a model to simulate depressurization of multiple segments exposed and unexposed to fire.

When comparing results of standardised values for exposure by fire after NORSOK S-001 to results simulated in this thesis, some differences are found. The most surprising is that S-001 is not always conservative, when compared to time to rupture in scenario 2 and 3 for smaller pipes and leak rates less than 2 kg/s. Standardized values for heat flux will not be specific for the geometry used, therefore would some differences be expected.

Depressurization after API (7.9 barg after 15 minutes) could result in escalation, when smaller pressurized pipes is exposed for heat flux over 300 kW/m^2 for more than two minutes The remaining pressure when rupture occurs is expected to be high, causing a larger release flow to form.

How a jet fire will behave could in many cases be dependent on the geometry. When a jet fire is directed into larger objects, the location of hot spots (peak heat flux values) on pipes and nearby equipment will not vary significantly, with time and strength in the release for the chosen scenarios. The values for global and peak flux will actually in some cases be almost constant. Objects can work as flame stabilizers. However, when the jet is unaffected by objects the hot spots could move over larger distances as the release flow decreases. Exposure of peak values placed on the same location on pipes or vessels could therefore be conservative.

A reduction in temperature is a result of fast depressurization. A reduction in temperature could cause a phase shift (gas condensates to liquid) to occur. This phenomenon and the low temperature should be further evaluated (the temperature is expected to be considerable lower than the minimum design temperature for several minutes) through a risk analysis. To better be able to predict the effect this would have on pipes and other affected pressurized equipment.

When a jet fire passes objects the heat flux may increase on the other side as a result of increased turbulence. Increased turbulence could lead to an increase in heat flux for equipment located on the other side. This is a phenomenon that should be considered, when designing/engineering new process plants or segments.

9 Reference

[1] NORSOK standard; Technical safety S-001, edition 4, February 2008.

[2] NORSOK standard; Technical safety S-001N, edition 3, January 2000.

[3] Confidential Gassco rapport nr. ST-20854-RA-1-Rev03. June 2007.

[4] Confidential Gassco rapport nr. RP-06-50715-01. October 2006.

[5] COMPUTIT (June 2001) by B.E. Vembe, K.E Rian, J.K. Holen, N.I. Lilleheie, B. Grimsmo and T. Myhrvold, Kameleon FireEx 2000 Theory Manual. Report no R0123.

[6] Ivar S. Ertesvåg (2000); Turbulent strømning og forbrenning. ISBN: 82-519-1568-6.

[7] Det Norske Veritas AS, Energy Report; Recommended failure rates for pipelines. Report no. 2009-1115, rev 01 2010-11-16.

[8] COMPUTIT (February 2010) by B.E. Vembe, K.E Rian, N.I. Lilleheie, B. Grimsmo, R. Olsen, B. Lakså, V. Nilsen, J. E. Vembe and T. Evang, Kameleon FireEx 2010 User Manual. Report no R0921.

[9] Statoil, *High pressure venting system*, System and operation document, SO0153, Final Ver. 1, Valid from 2004-12-02.

[10] Scandpower (March 2004); Guidelines for the Protection of pressurised System Exposed to Fire, report nr. 27.207.291/R1 – Version 2.

[11] Confidential Gassco, June 2005-01-13

[12] Confidential Gassco , rapport nr D024-A-500-S-RS-007

[13] «TNO Yellow Book», Methods for the calculation of Physical Effects Due to releases of hazardous materials. Editors: C.J.H. van den Bosch, R.A.P.M. Weterings (1996).

[14] Bjarne Christian Hagen (2004); Grunnleggende brannteknikk. ISBN: 82-996645-1-9.

[15] Confidential Gassco rapport nr. 060109.docx, edition 4. Aug 2011.

[16] Petrell, (Revision date, March 2009) by AK, AB og GB (Geir Berge), Vessfire User manual for version 1.2.

[17] H.K. Versteeg and W. Malalasekera. An Introduction to Computational Fluid Dynamics. Pearson Education Limited, 2nd edition, 2007.

[18] Yeoh and Yuen, 2009; Computational Fluid Dynamics in Fire Engineering. ISBN: 978-0-7506-8589-4

[19] HSE; Health and Safety Executive definitions: http://www.hse.gov.uk/offshore/strategy/jet.htm (downloaded 5.1.2013)

[20] Bjørn Erling Vembe (2012); Simulering av realistiske og detaljerte varmelaster ved brann I prosessanlegg. Hva kan vi lære? http://www.tekna.no/ikbViewer/Content/859597/01_Computit_tekna_nov2012_utenfilm_Vembe.pdf (downloaded 15.1.2013)

[21] Rolf K. Eckhoff (2005); Explosion Hazards in the process industries. ISBN: 0-9765113-4-7.

[22] Trevor Kletz (2009); What Went Wrong? Case histories of process plant disasters and how they could have been avoided, fifth edition, ISBN 13: 978-1-85617-531-9

[23] Mark J. Swift og Kirill V. Horoshenkov (2009); Termiske og akustiske egenskaper for elastomer rørisolasjon: http://www.akustisk-selskap.com/old/NAS_revised/Webpages/Artikler/sammendrag113.pdf

[24] YARAPRAXAIR; Gass farer og gassikkerhet. Version 2

http://www.yarapraxair.no/Global/Norway/Brosjyrer/HMS/Gassfare%20og%20gassikkerhet.pdf (downloaded 21.1.2013)

[25] Nasar Badri, Amirhosein Rad, Hamid Kareshki, Bahman Abdolhamidzadeh, Roghaieh Parvizsedghy and Davood Rashtchian; Journal of loss prevention in the process industry; (Jan. 2013) A risk-based decision making approach to determine fireproofing requirements against jet fire.

[26] The Engineering Toolbox; http://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html (downloaded 3.5.2013).

[27] Dougal Drysdal (March 2008); An introduction to Fire Dynamics, second edition. ISBN: 978-0471-7

10 Attachments/ Appendix

Appendix A. A part of a Vessfire simulation report (Scenario 2).

In this appendix an extract from scenario 2 simulated in Vessfire is shown, this to present some curves an simulation input that could be of interest, and to show how the result is presented when a simulation is completed.

Vessfire Simulation Report scenario 2

Report generated: 28.01.2013 18:56:04

Rupture summary

Time (min)	Element	Pressure (kPa)	Comments
2,22605	2-GN-525-2-318-DC93	6 569,97	Too early rupture: 2,22605 min vs. 3 min. Too high pressure: 6 569,97 kPa vs. 2 101,32 kPa. Too much gaseous hydrocarbons in segment: 3 258,02 kg vs. 1 000 kg.
5,81944	3-GN-525-2-314-DC93	727,506	Rupture is acceptable; note that VessFire does currently *not* account for gases flashing at rupture, so the gas mass may be underestimated.

Case Definition

Vessel Cyclone_seperatorT-2

- Flame:
  - Longitudinal start: 90 %
  - Longitudinal end: 100 %
  - Angle from top: 0°
  - Exposed arc: 30°

    - Impinging Flame: Yes
- First blow-down valve:
    - Diameter: 0,0273915 m
    - Contraction factor: 84 %
    - Delay: 0 min
- BDV position:
    - Longitudinal: 100 %
    - Angular (from top): 0°
- Blow-down line:
    - Diameter: 0,0889 m
    - Wall thickness: 0,0071 m
    - Length: 5,5 m
- External longitudinal stress: 0 MPa
- Stress factor: 95 %
- Failure criterion: UTS
- Material: CS_360LT
- Material strength: 625 MPa
- Outer diameter: 1,34 m
- Wall thickness: 0,055 m
- Corrosion allowance: 0 m
- Length: 2,598 m
- Operating pressure: 12 101,3 kPa
- Operating inventory temperature: 0 °C
- Operating shell temperature: 0 °C
- Hydrocarbon level: 0,1 m
- Water level: 0 m
- Backpressure: 101,325 kPa
- Environment temperature: 10 °C
- Emissivity: 85 %
- Orientation: Vertical

Pipes

- Common pipe data:
    - Heat load "HT1"
        - Environment temperature: 10 °C
        - Emissivity: 85 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "HT2"
        - Environment temperature: 10 °C
        - Emissivity: 85 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "HT3"
        - Environment temperature: 10 °C
        - Emissivity: 85 %

        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "HT4"
        - Environment temperature: 10 °C
        - Emissivity: 85 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "HT1PEAK"
        - Environment temperature: 10 °C
        - Emissivity: 85 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "HT3PEAK"
        - Environment temperature: 10 °C
        - Emissivity: 85 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "HT5"
        - Environment temperature: 10 °C
        - Emissivity: 70 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "Zero"
        - Environment temperature: 10 °C
        - Emissivity: 85 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Heat load "HT9"
        - Environment temperature: 10 °C
        - Emissivity: 85 %
        - Heat-transfer coefficient: 100 W/m² K
        - Impinging Flame: Yes
    - Maximum ruptured pipes: 0
    - Contraction factor: 80 %
- Pipe 24-GN-525-2-305-DC93-1
    - Material: CS_360LT
    - Outer diameter: 0,61 m
    - Wall thickness: 0,0305 m
    - Length: 5,5 m
    - Mill tolerance: 0 %
    - Corrosion allowance: 0 m
    - Peak load: HT3PEAK, see common data
    - Background load: HT3, see common data
    - Material strength: 500 MPa
    - External longitudinal stress: 0 MPa
    - Stress factor: 95 %
    - Rupture criterion: UTS

  - Initial inventory temperature: 0 °C
  - Initial shell temperature: 0 °C
  - Phase: gas
- Pipe 24-GN-525-2-305-DC93-2
  - Material: CS_360LT
  - Outer diameter: 0,61 m
  - Wall thickness: 0,0305 m
  - Length: 2,44 m
  - Mill tolerance: 0 %
  - Corrosion allowance: 0 m
  - Peak load: HT3PEAK, see common data
  - Background load: HT5, see common data
  - Material strength: 500 MPa
  - External longitudinal stress: 0 MPa
  - Stress factor: 95 %
  - Rupture criterion: UTS
  - Initial inventory temperature: 0 °C
  - Initial shell temperature: 0 °C
  - Phase: gas

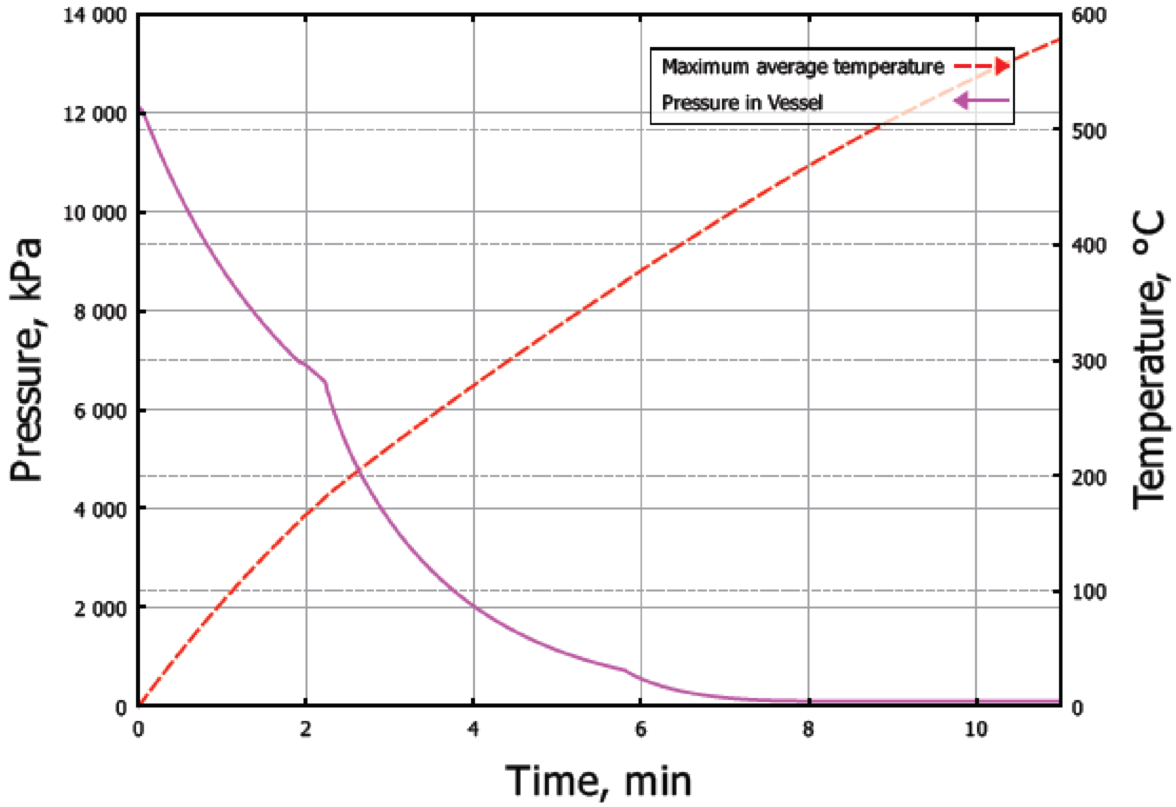


Figure 3: Pressure in the vessel

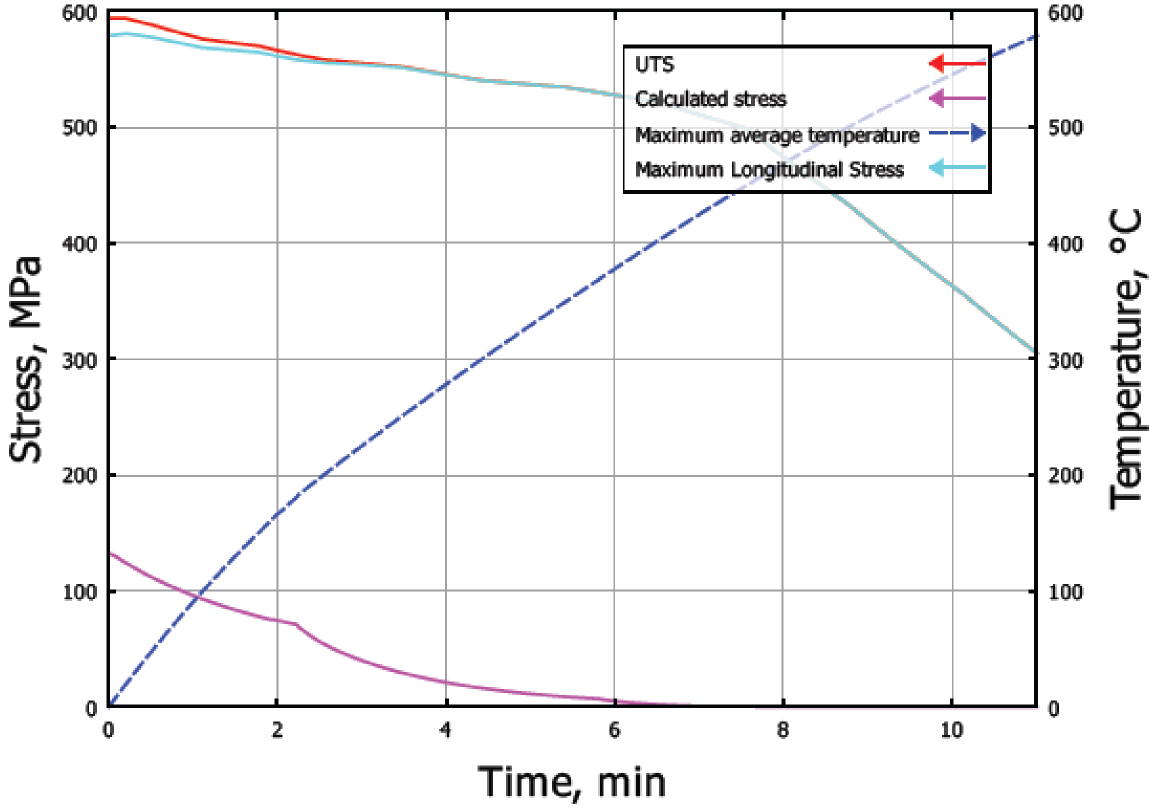


Figure 4: Stress in the vessel

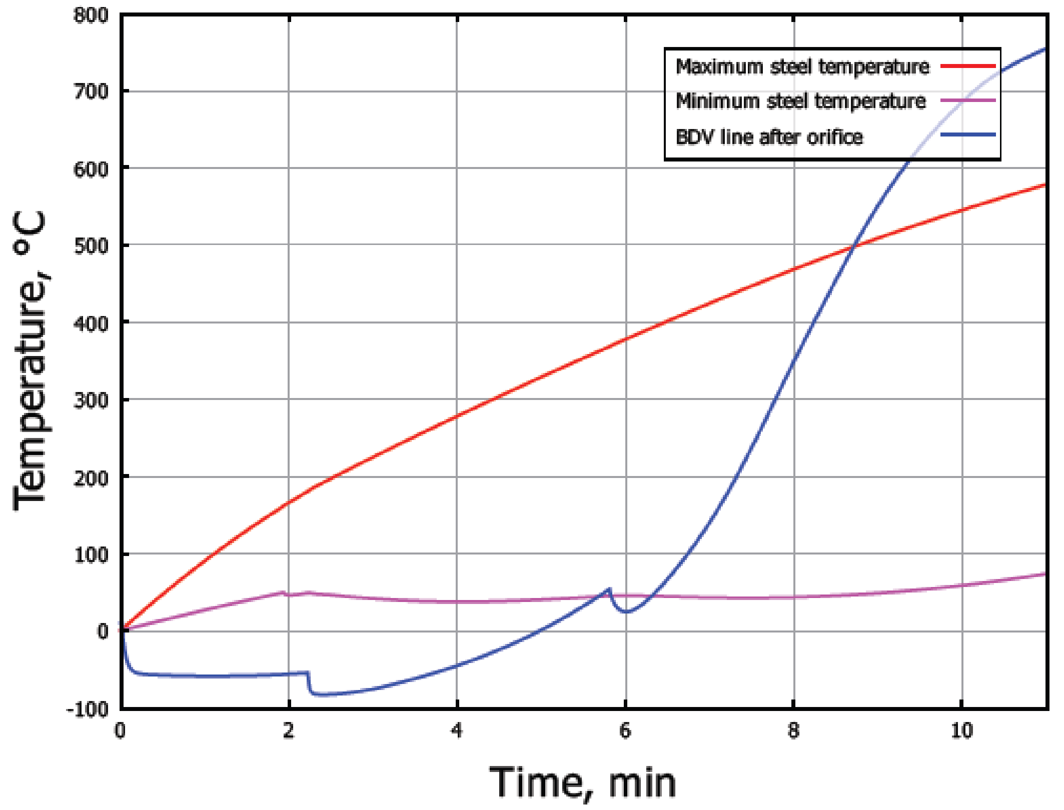


Figure 5: Steel temperatures

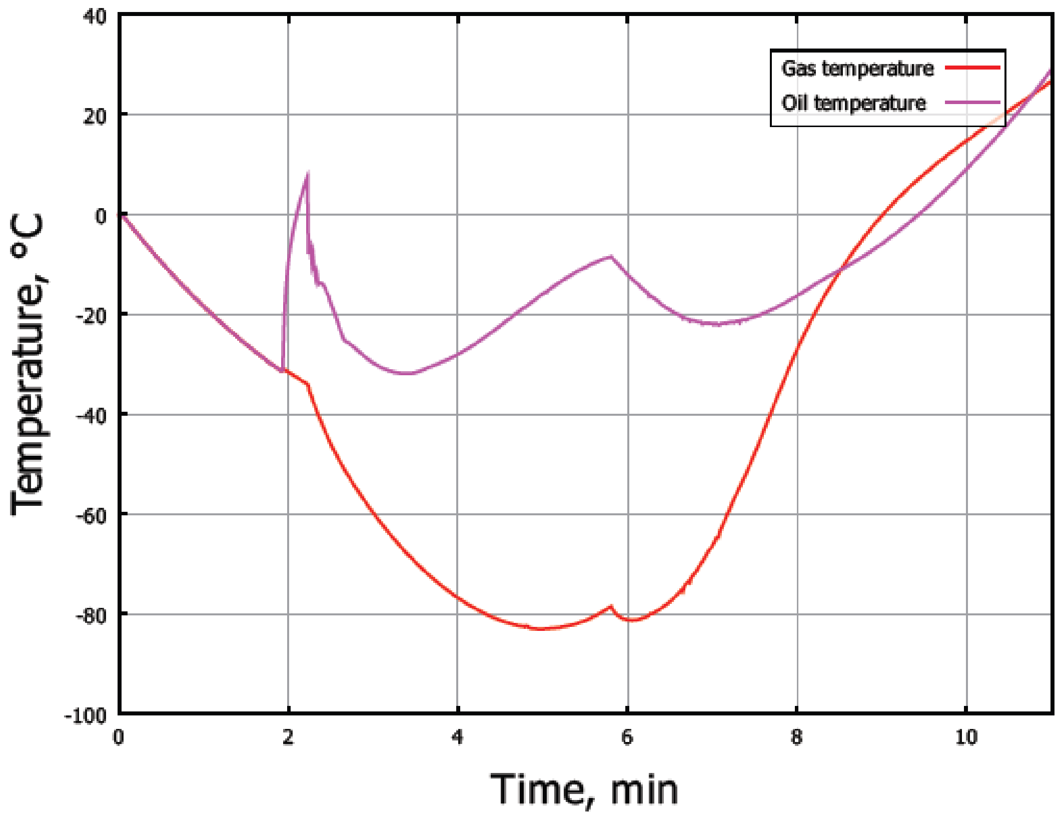


Figure 6: Content temperatures

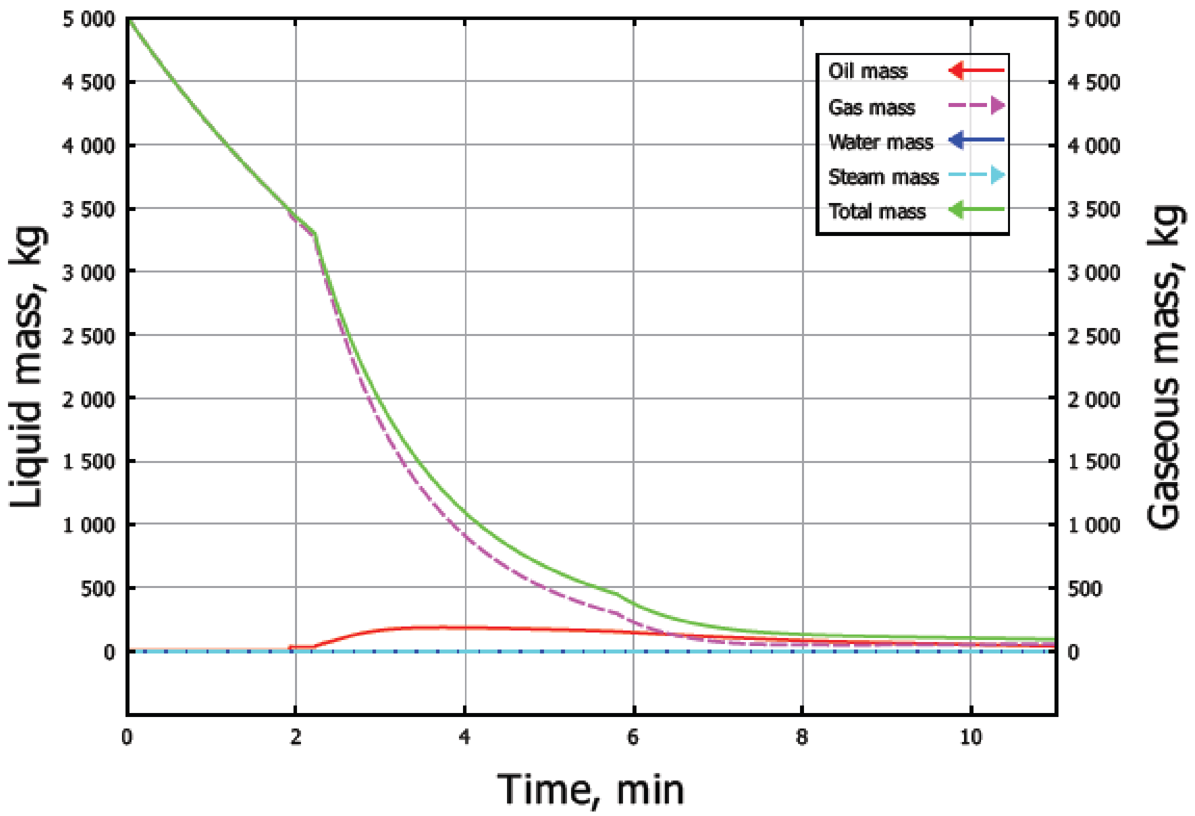


Figure 7: Segment masses

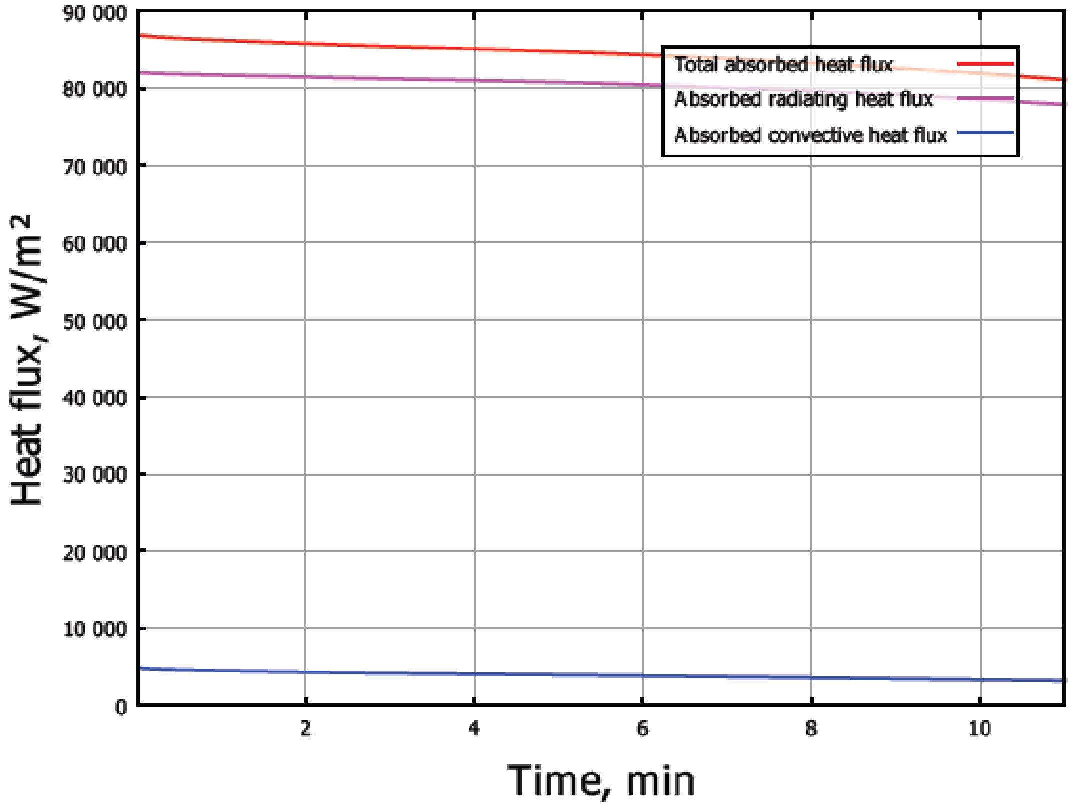


Figure 8: Absorbed heat flux

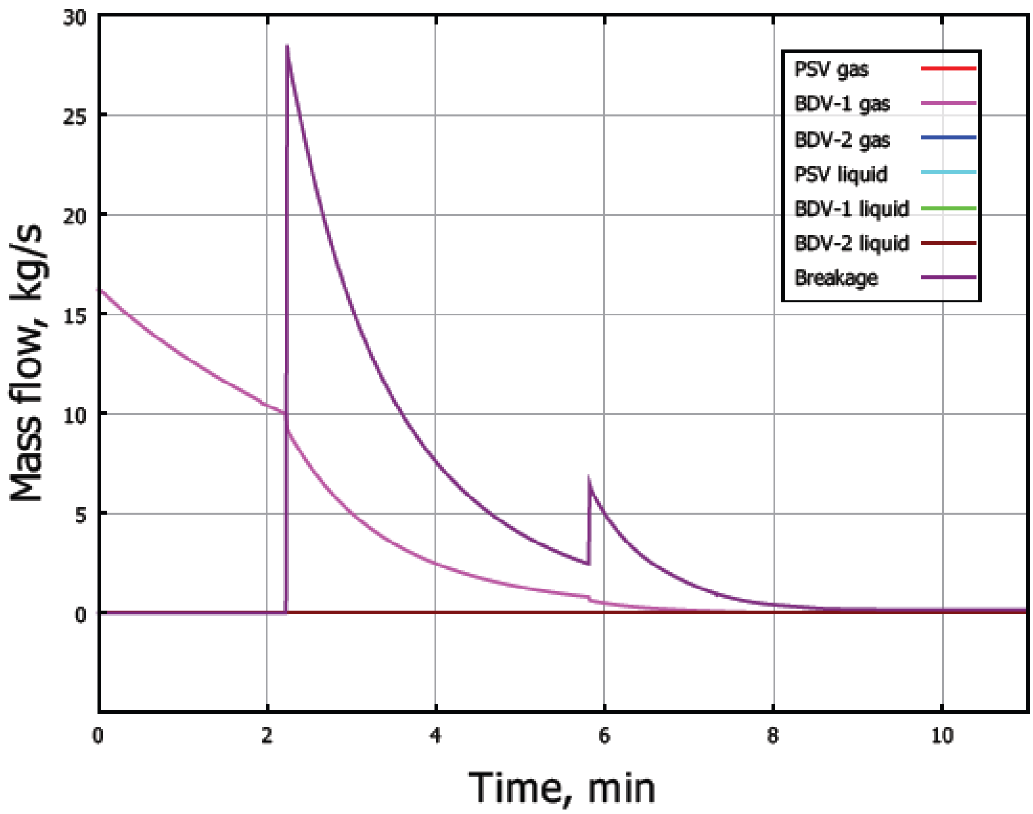


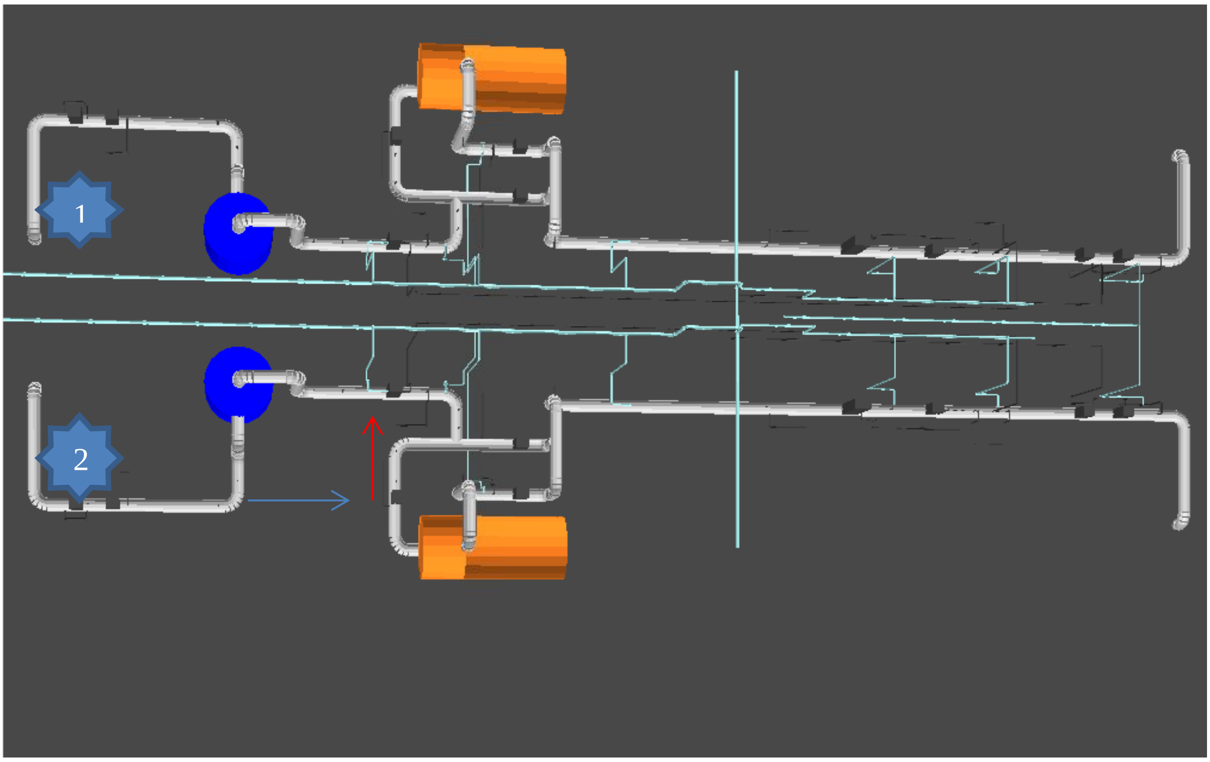
Figure 10: Valve flows

Appendix B. Kameleon KFX results phase 3.

In this appendix some results from scenario 2, phase 3 simulated in KFX will be presented. Underneath each picture there is a script, for example:

Time: 135 s, release flow: 28.38 kg/s

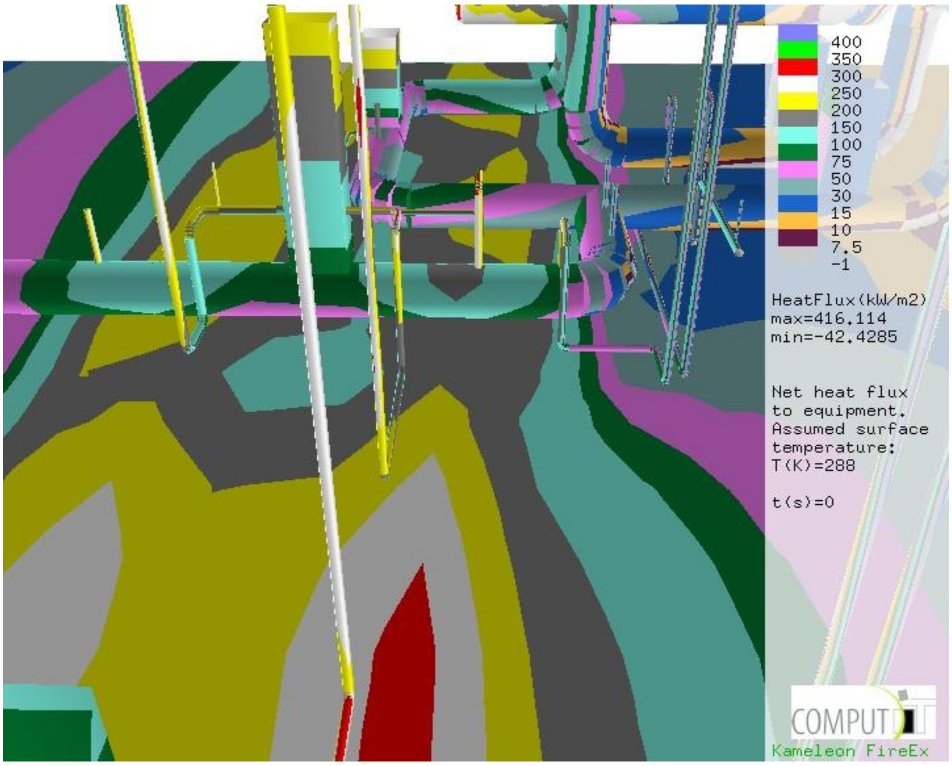
Here will the start of the initial leak in the first phase be taken into consideration and 28.38 kg/s is the release rate for the rupture.



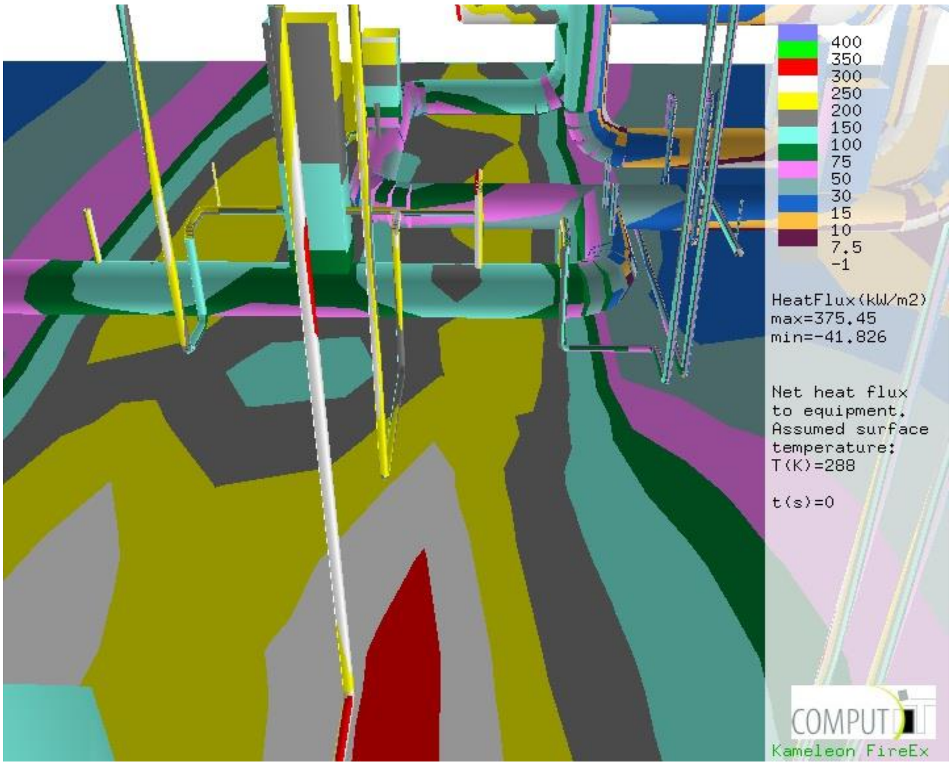
Train 1 is the upper process train in the figure above. The initial leak in scenario 2 is marked with a blue arrow, and the release direction of the 2” rupture is marked red. The pictures in this appendix shows (Escal2-5) is taken from the same area as the 2” rupture and directed towards train 1.

The pictures are taken from the same angel as the jet fires direction. The pictures shown here is only a sample of the results gathered, and shows the front of 2”GN-525-2-324-DC93, and the back side of 2”GN-525-1-324-DC93, whereas the last mention pipe located on train 1, is the pipe mention in phase 3 (both backside and front is evaluated when creating heat loads).

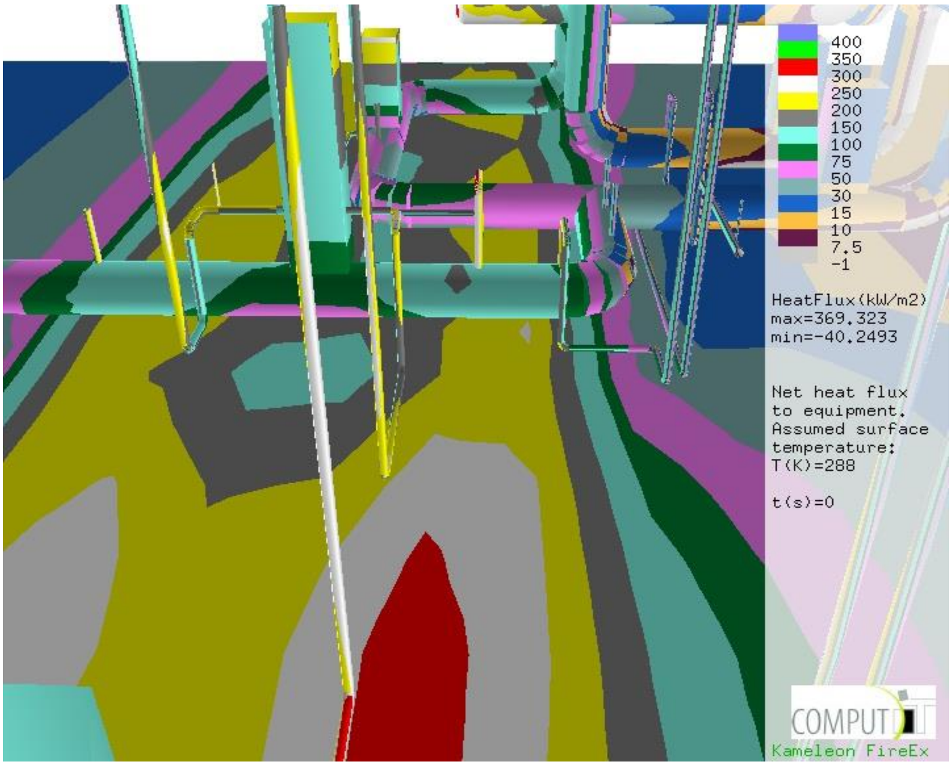
Escal2-5



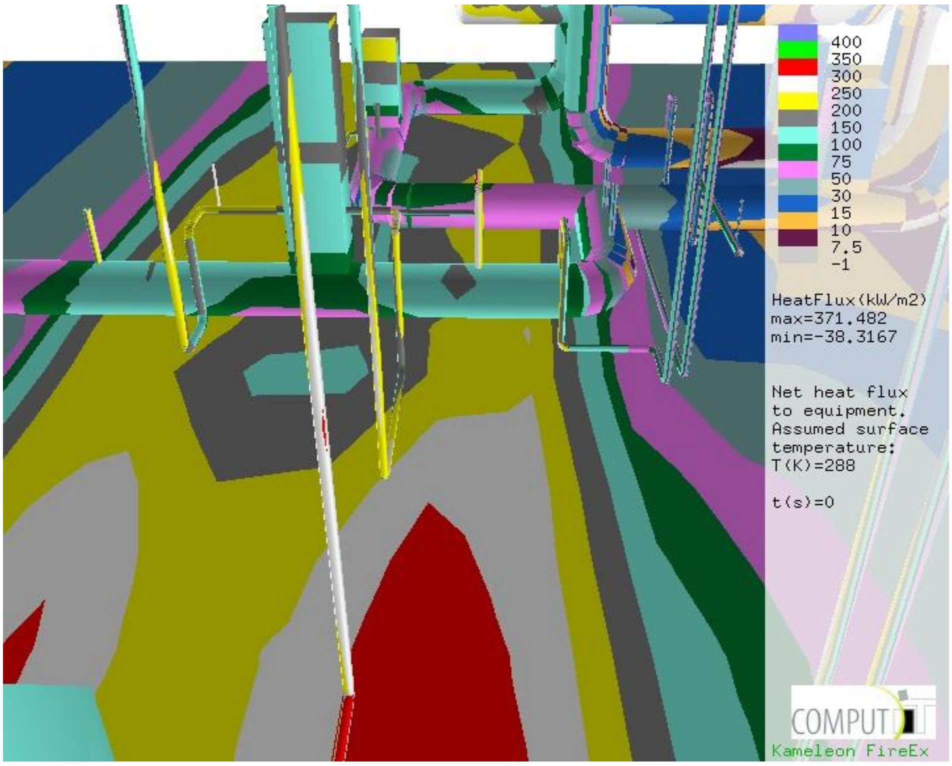
Time: 135 s, release flow: 28.38 kg/s



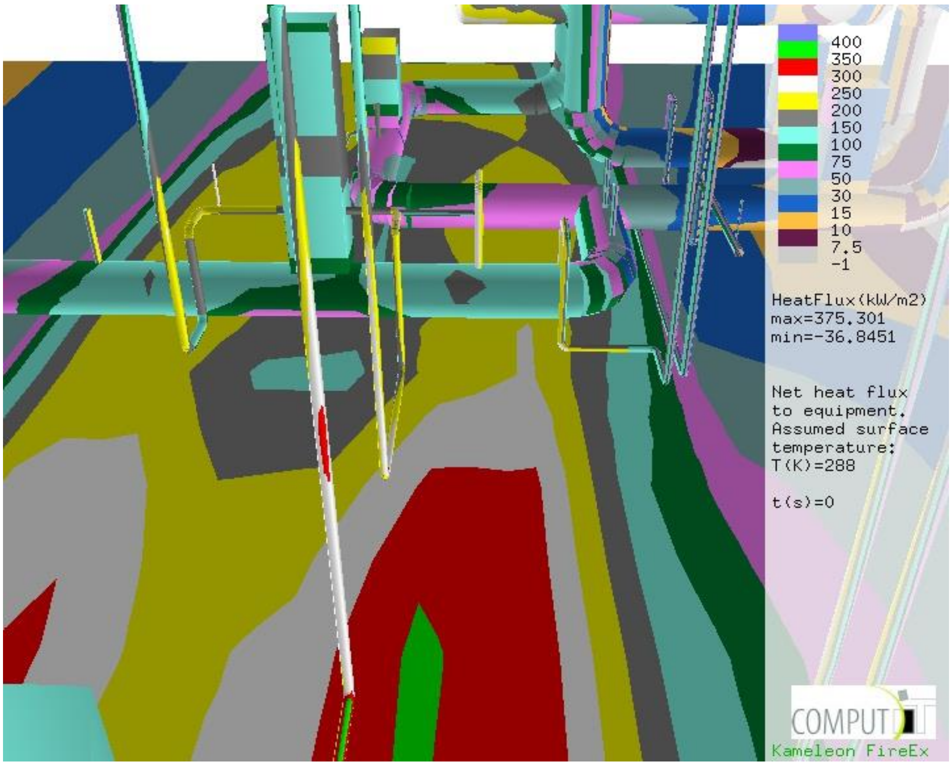
Time: 141 s, release flow: 26.8 kg/s



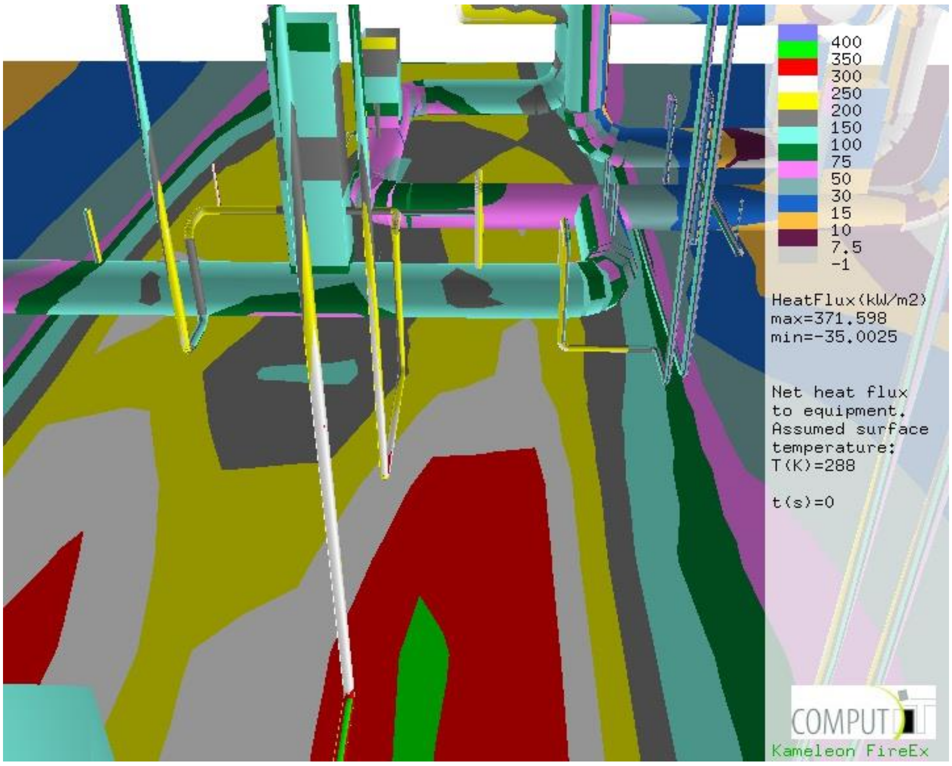
Time: 147 s, release flow: 24.74 kg/s



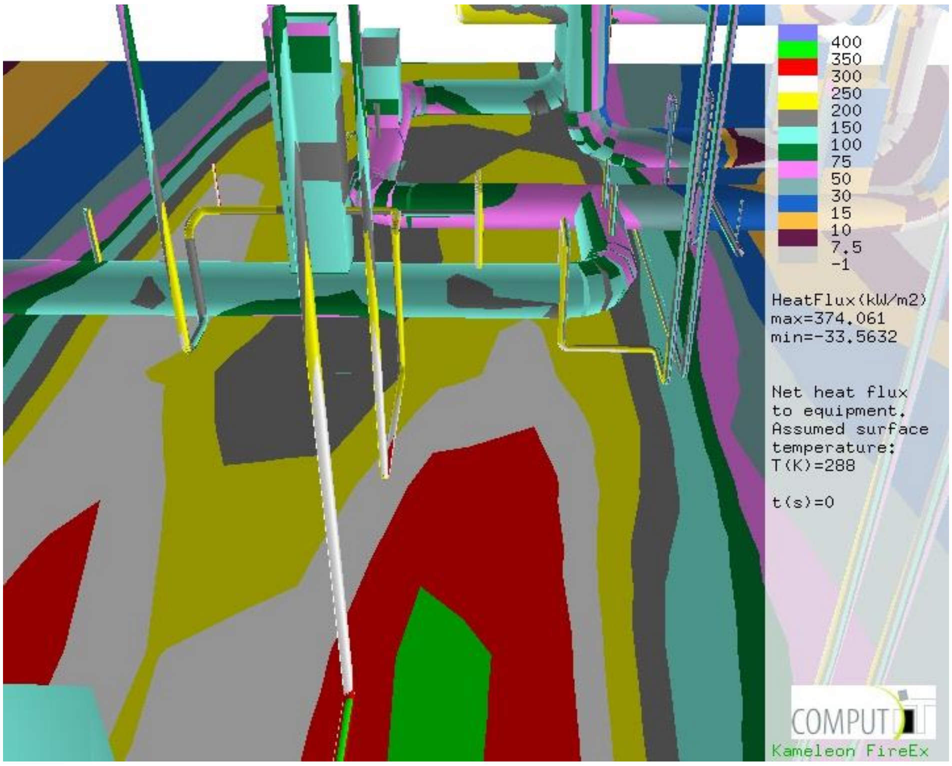
Time: 153 s, release flow: 22.8 kg/s



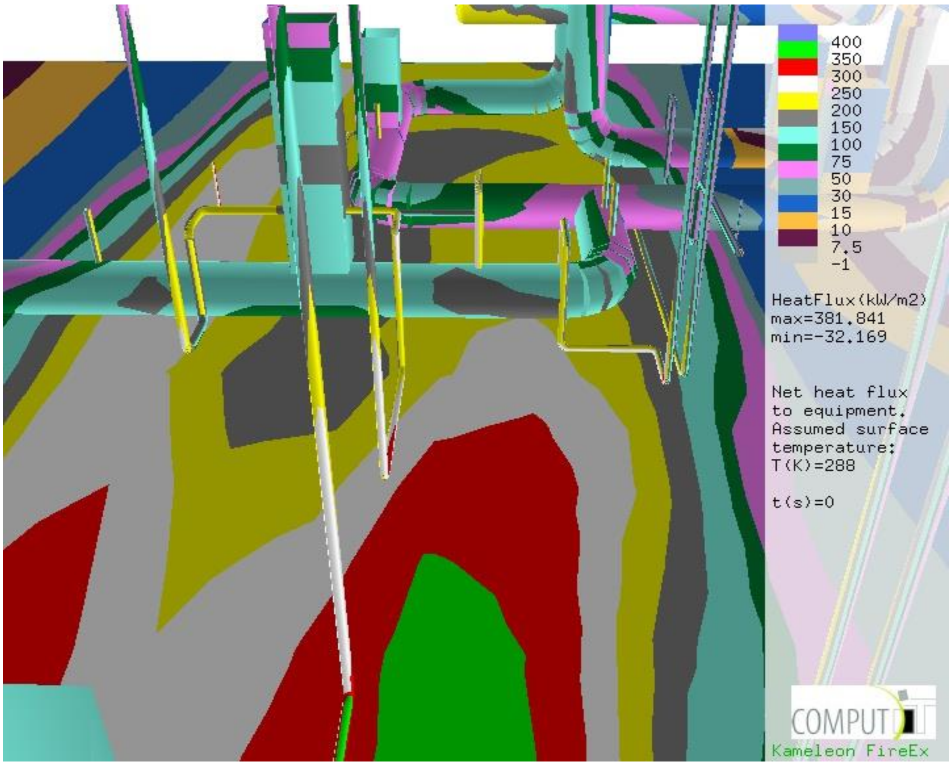
Time: 159 s, release flow: 21 kg/s



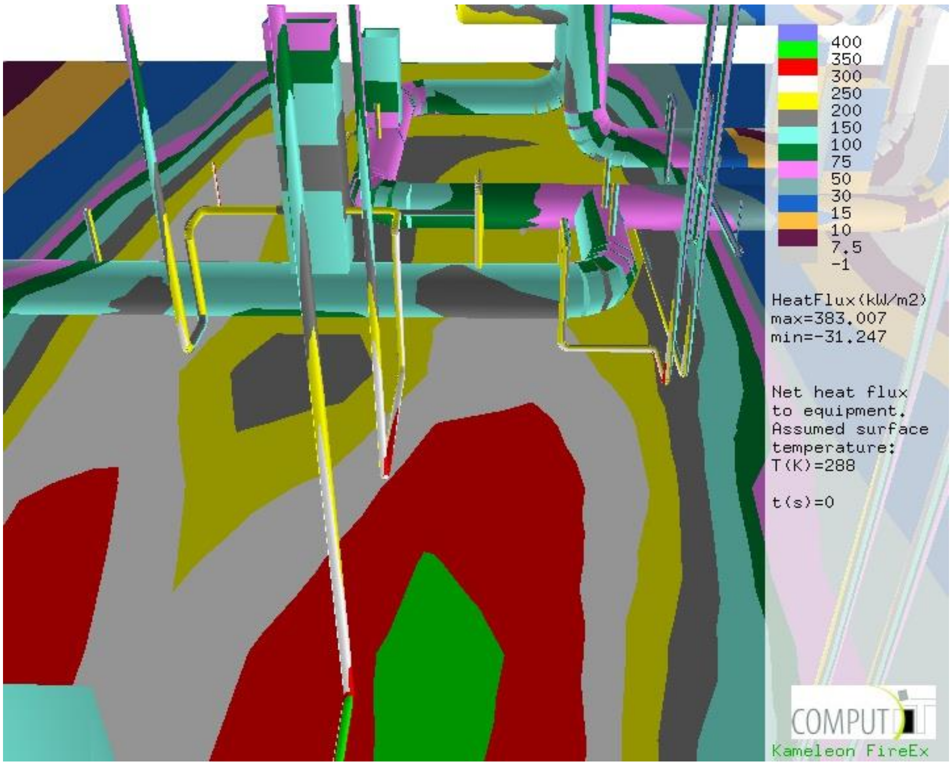
Time: 165 s, release flow: 19.4 kg/s



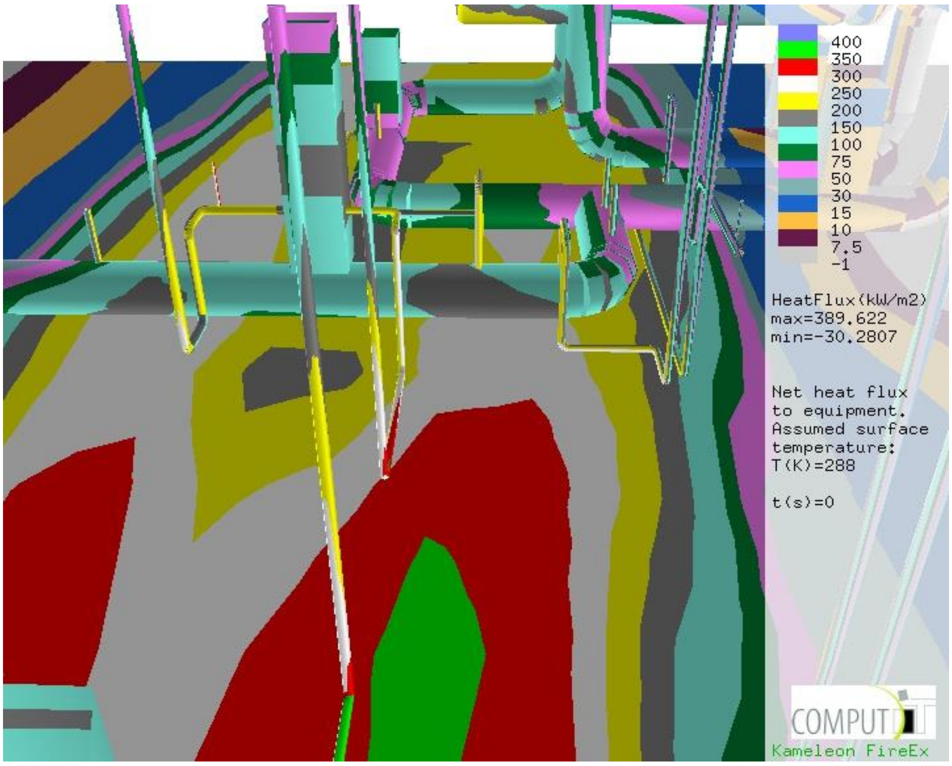
Time: 171 s, release flow: 18 kg/s



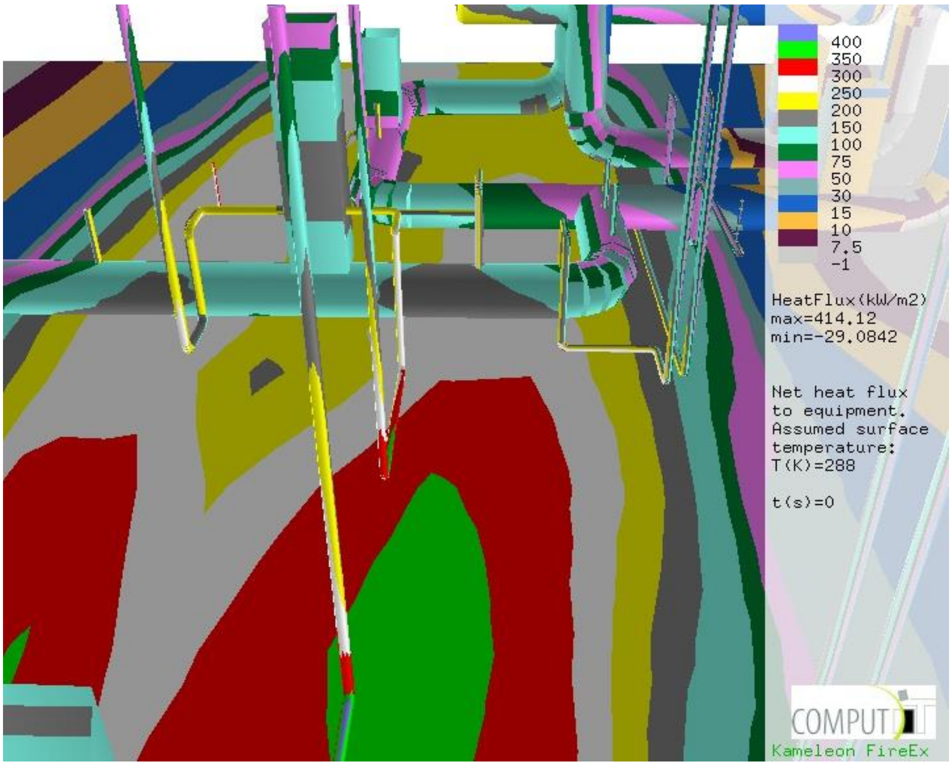
Time: 177 s, release flow: 16.63 kg/s



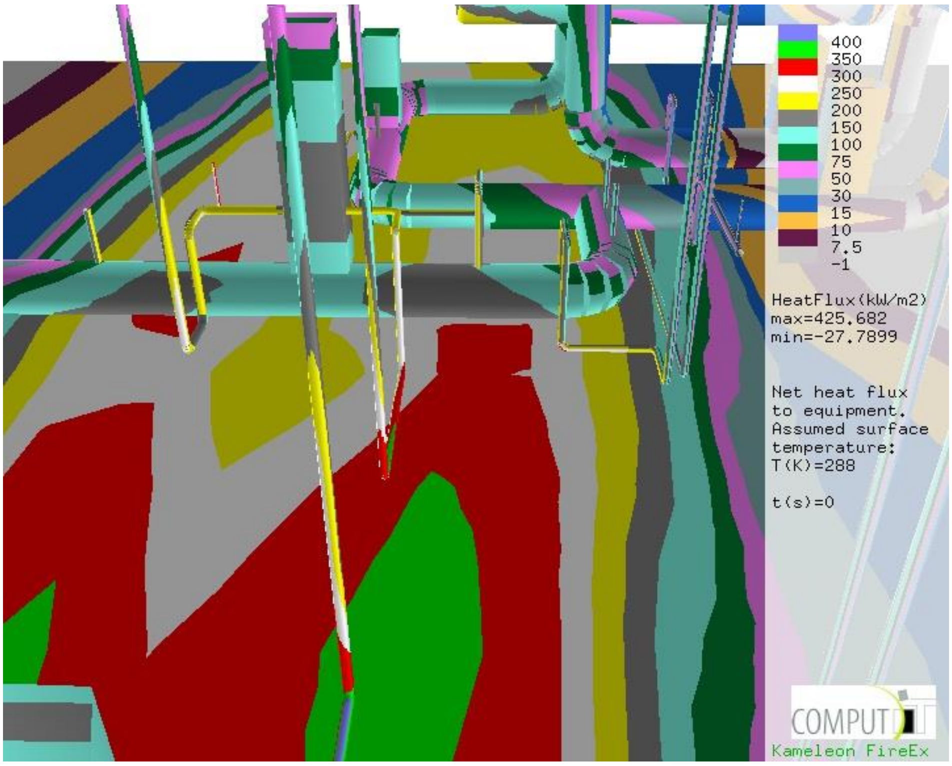
Time: 183 s, release flow: 15.4 kg/s



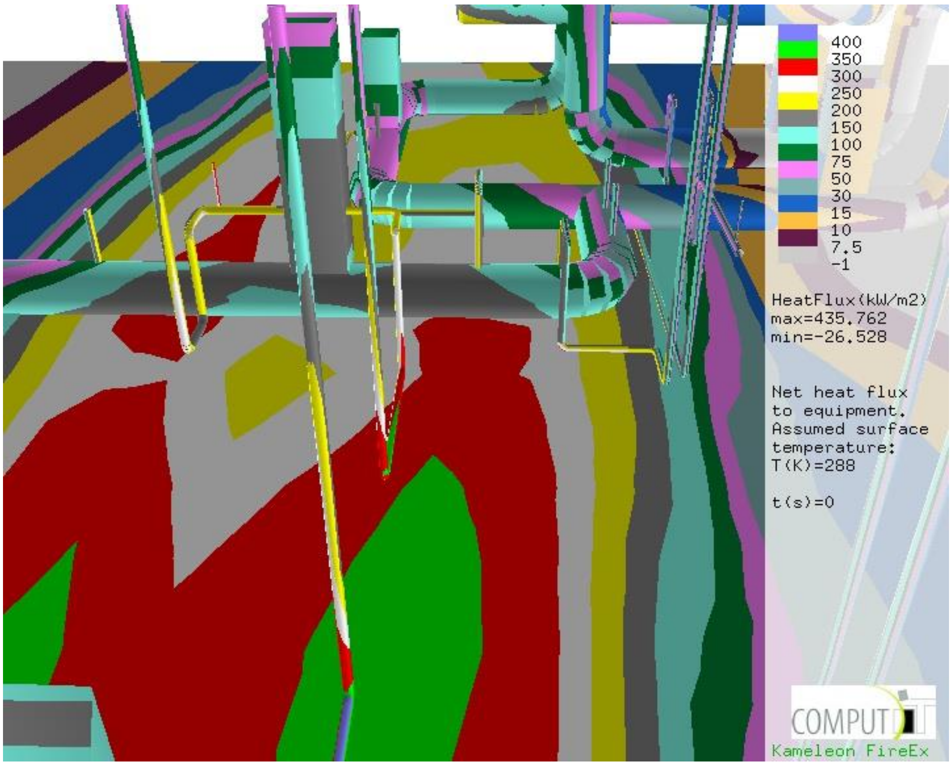
Time: 189 s, release flow: 14.3 kg/s



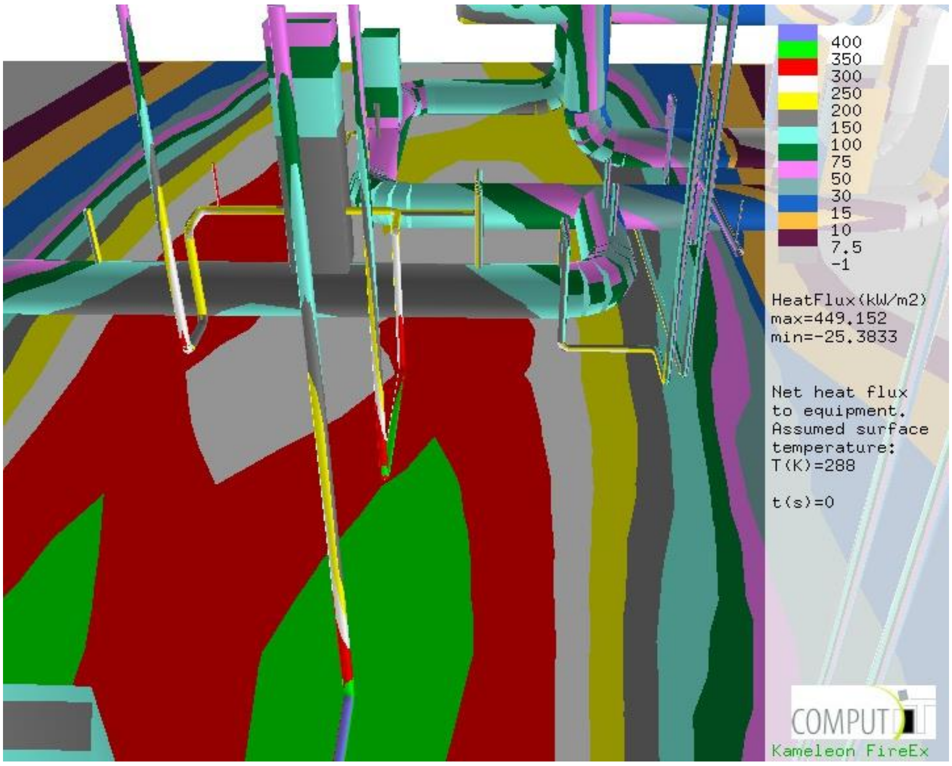
Time: 195 s, release flow: 13.3 kg/s



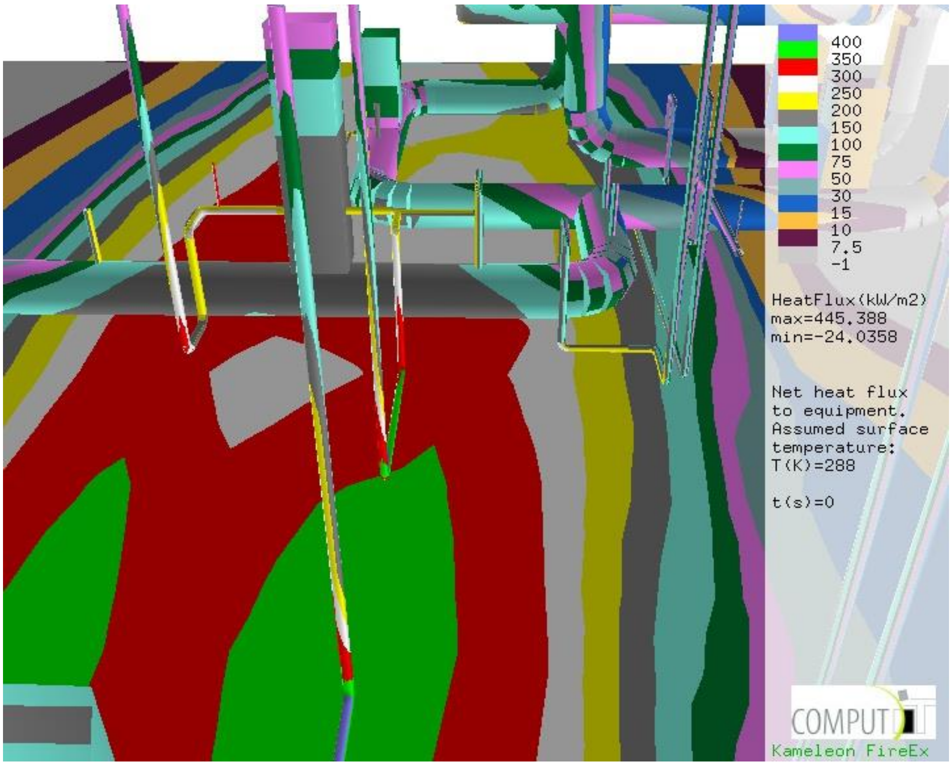
Time: 201 s, release flow: 12.32 kg/s



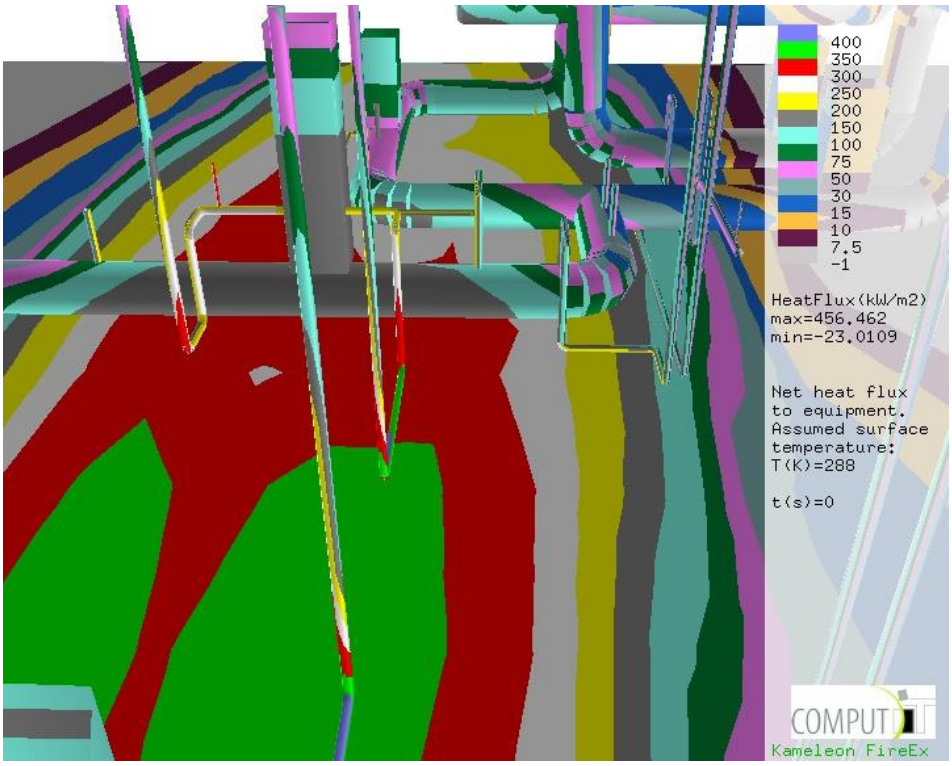
Time: 207 s, release flow: 11.5 kg/s



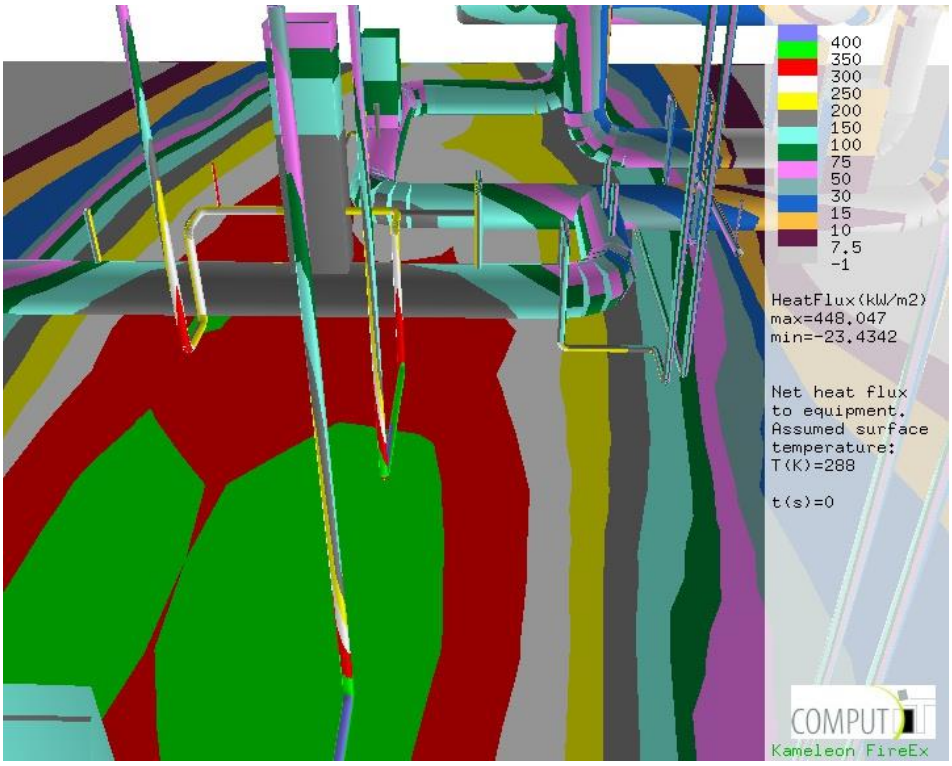
Time: 213 s, release flow: 10.7 kg/s



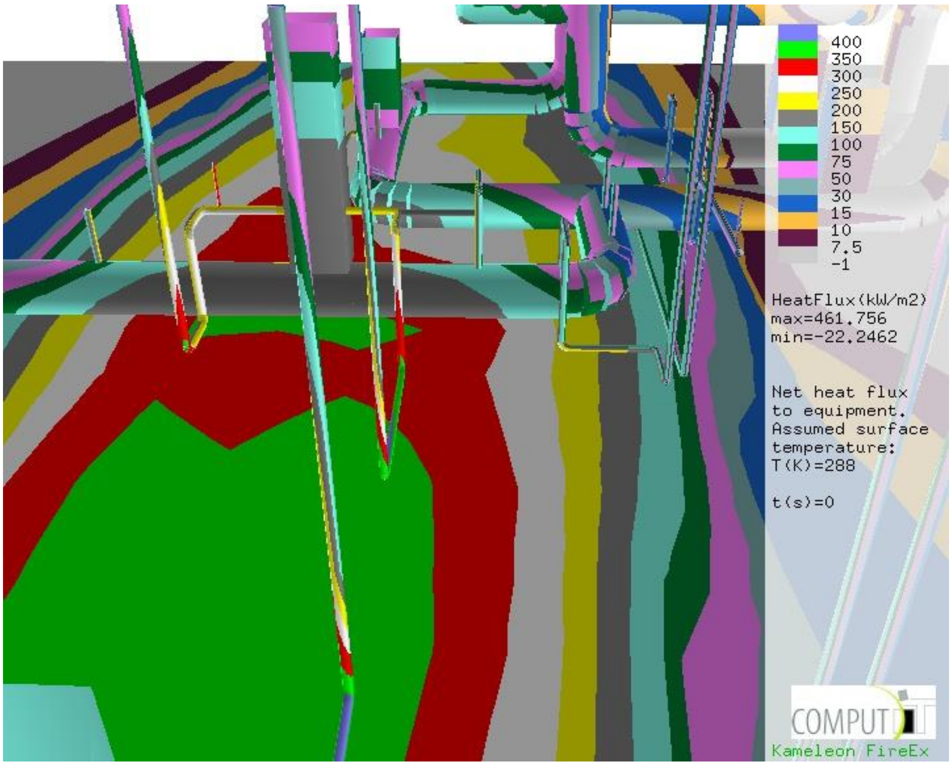
Time: 219 s, release flow: 10 kg/s



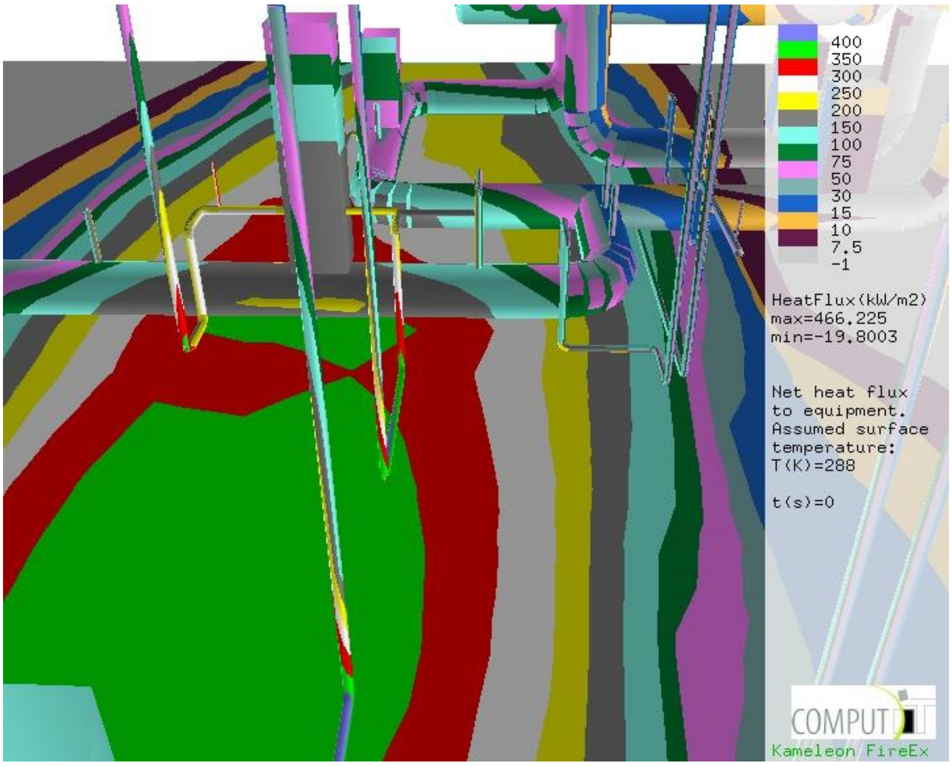
Time: 225 s, release flow: 9.32 kg/s



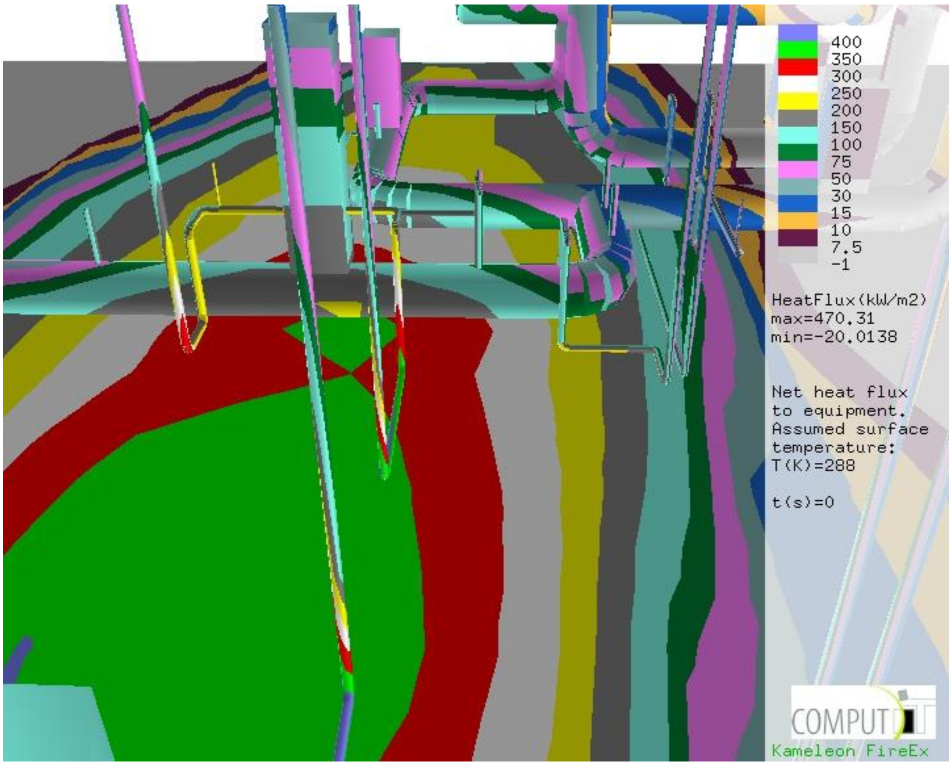
Time: 231 s, release flow: 8.7 kg/s



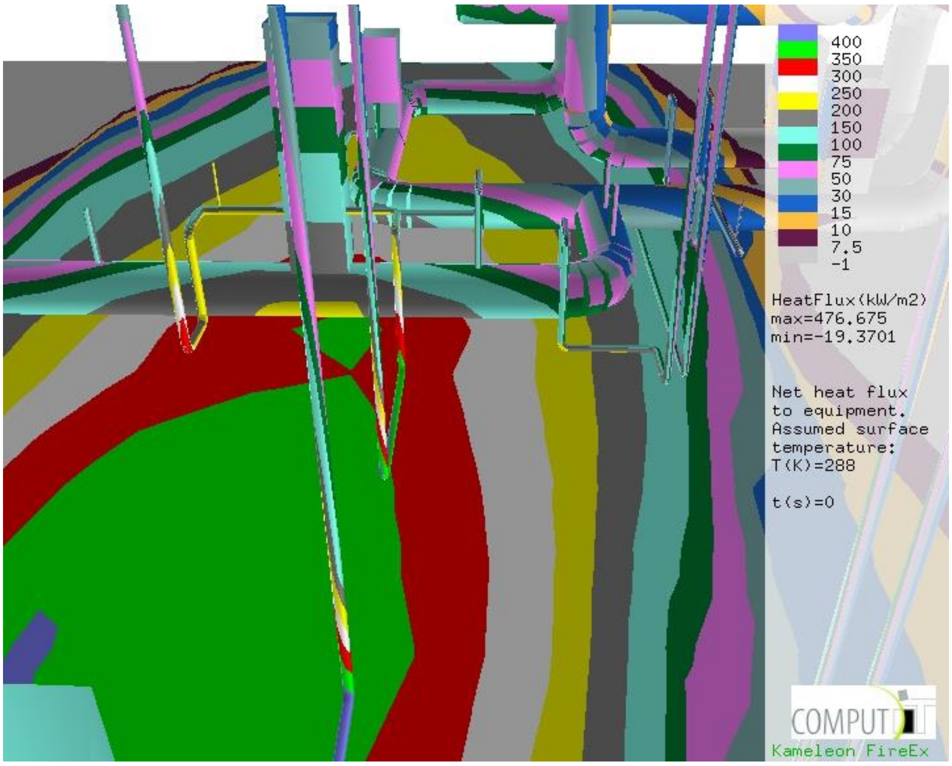
Time: 237 s, release flow: 8.13 kg/s



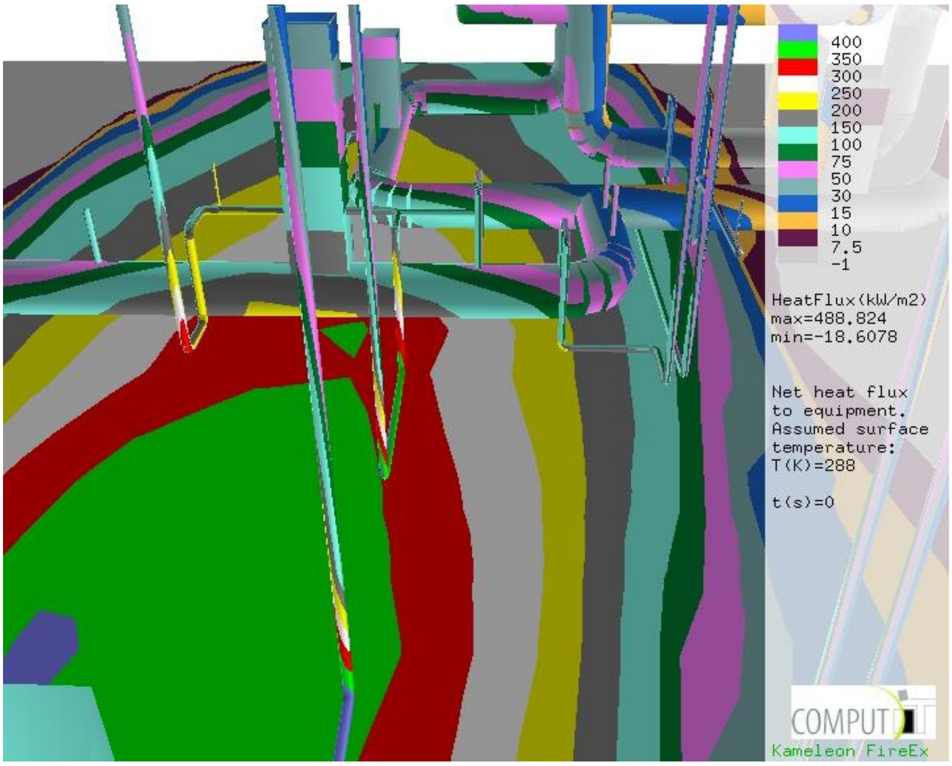
Time: 243 s, release flow: 7.6 kg/s



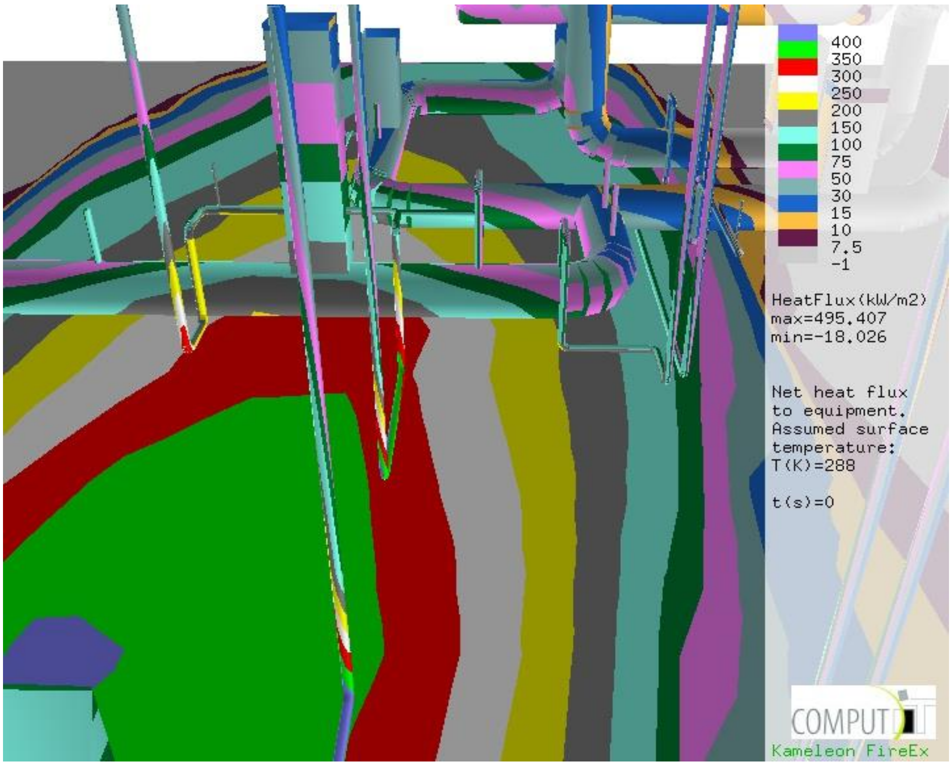
Time: 249 s, release flow: 7.11 kg/s



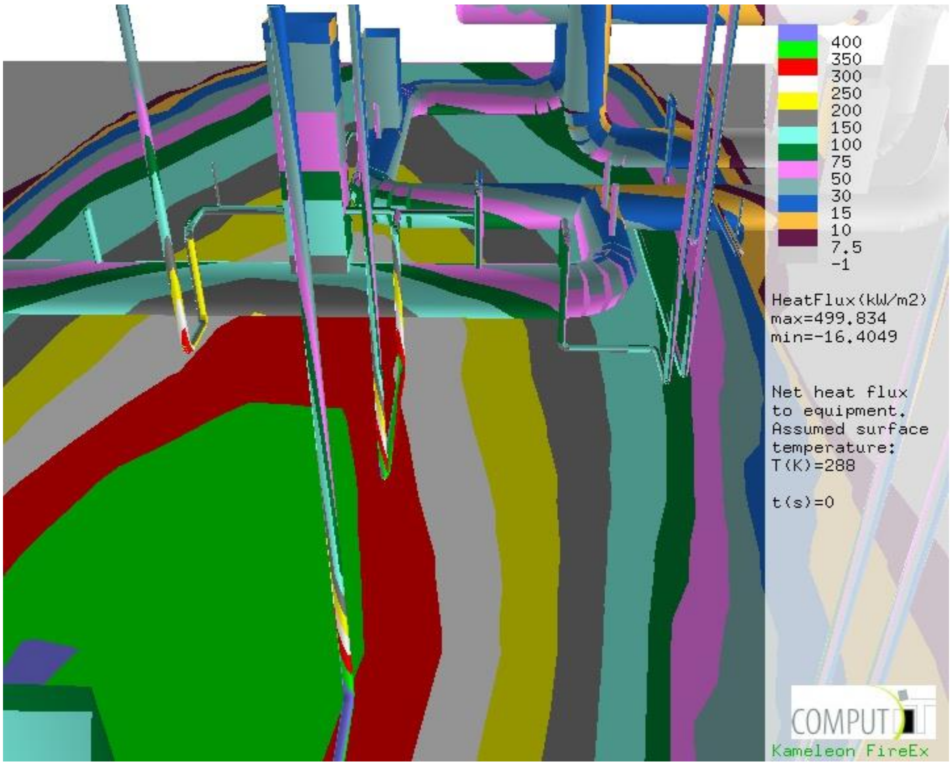
Time: 255 s, release flow: 6.65 kg/s



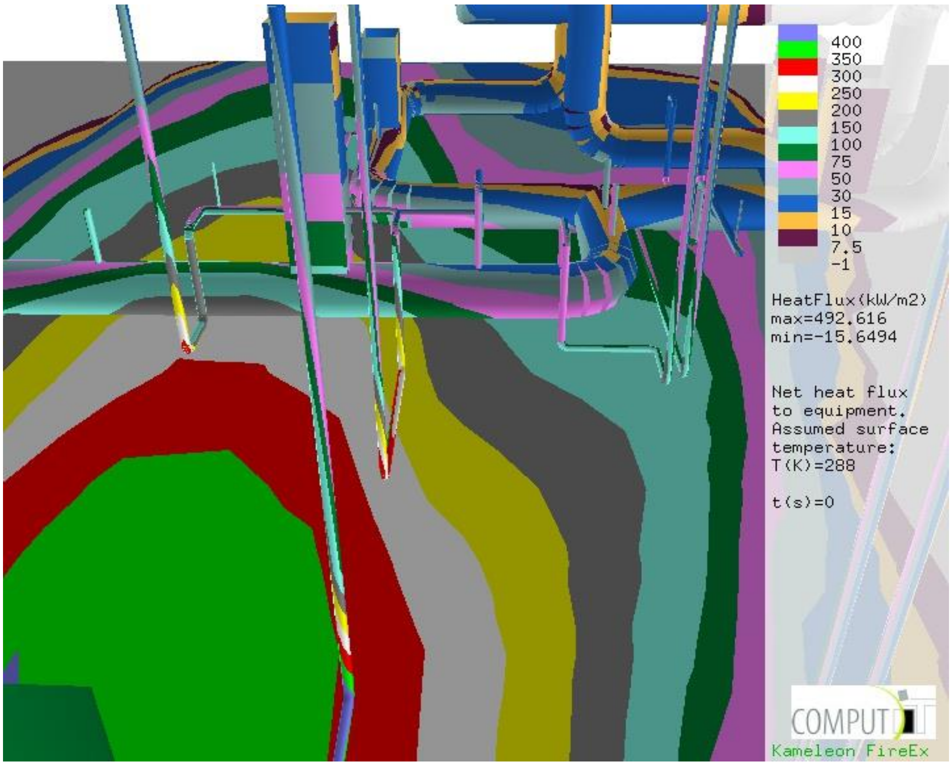
Time: 261 s, release flow: 6.23 kg/s



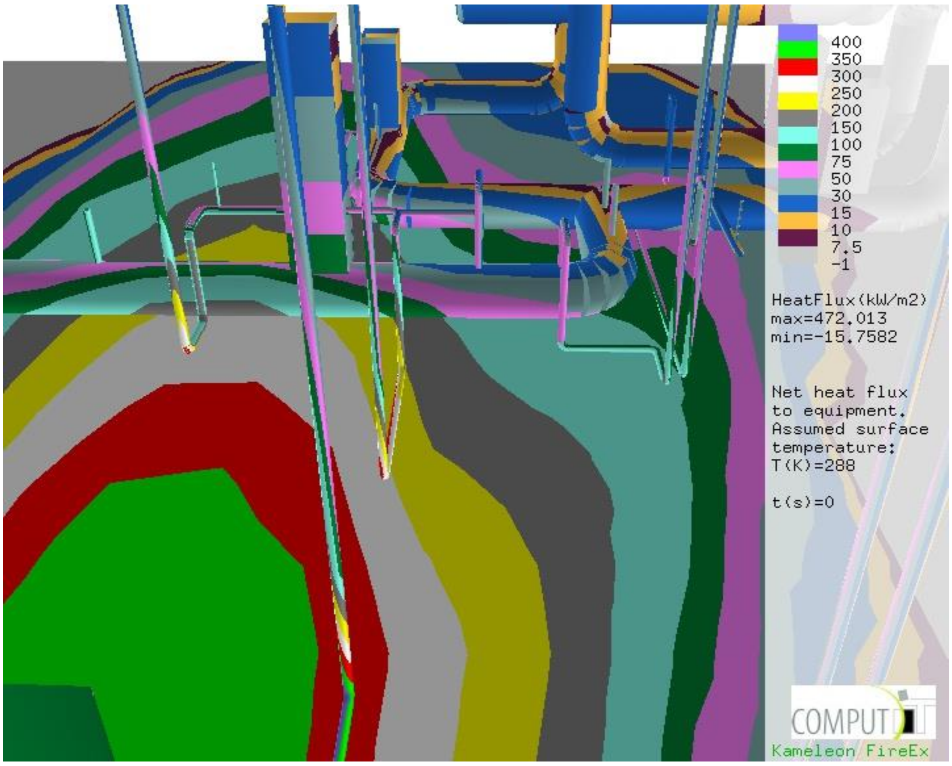
Time: 267 s, release flow: 5.84 kg/s



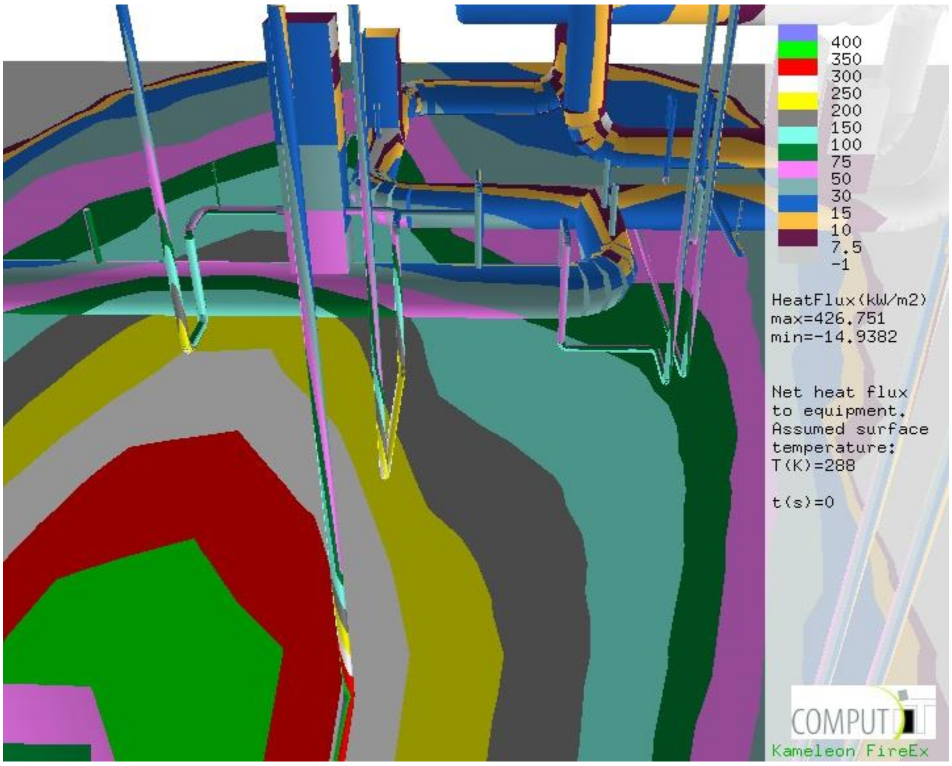
Time: 273 s, release flow: 5.48 kg/s



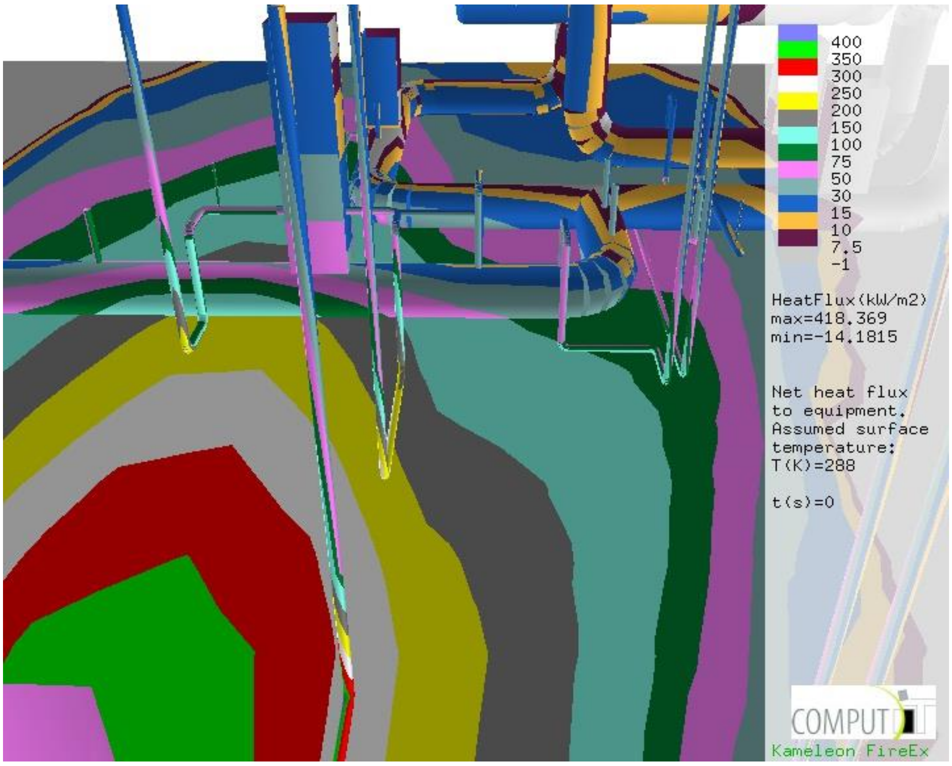
Time: 279 s, release flow: 5.14 kg/s



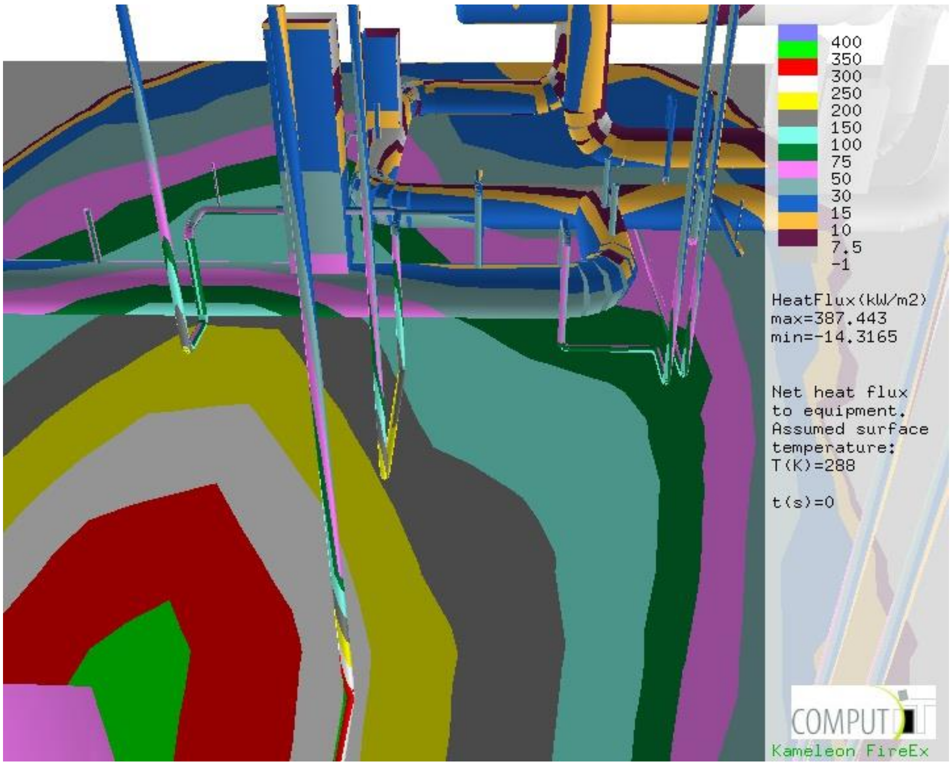
Time: 285 s, release flow: 4.82 kg/s



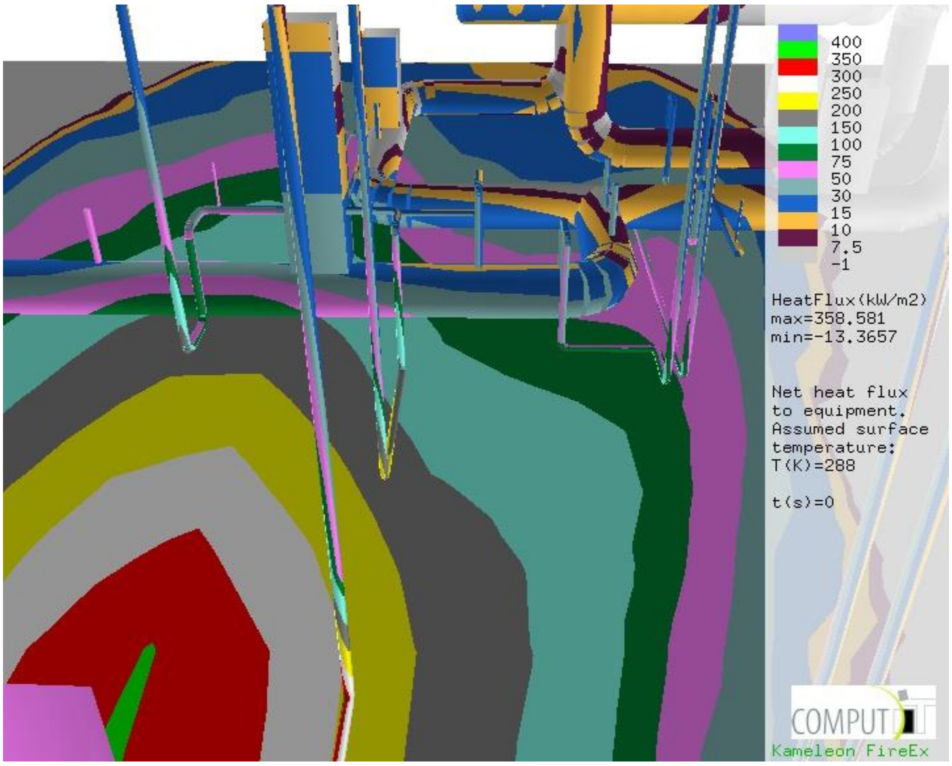
Time: 291 s, release flow: 4.53 kg/s



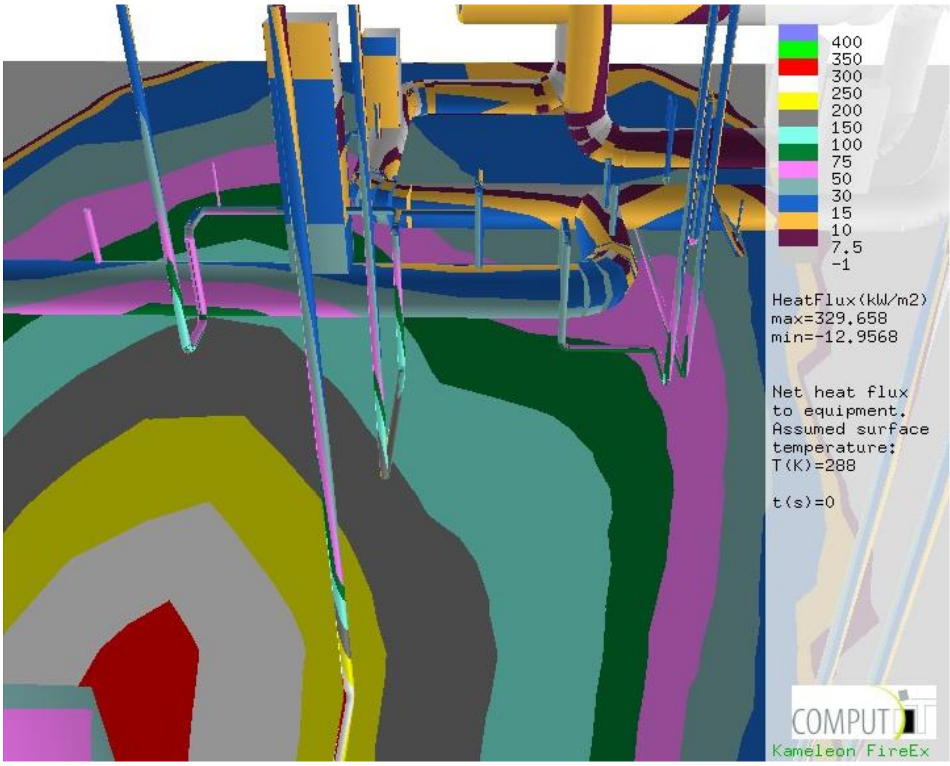
Time: 297 s, release flow: 4.25 kg/s



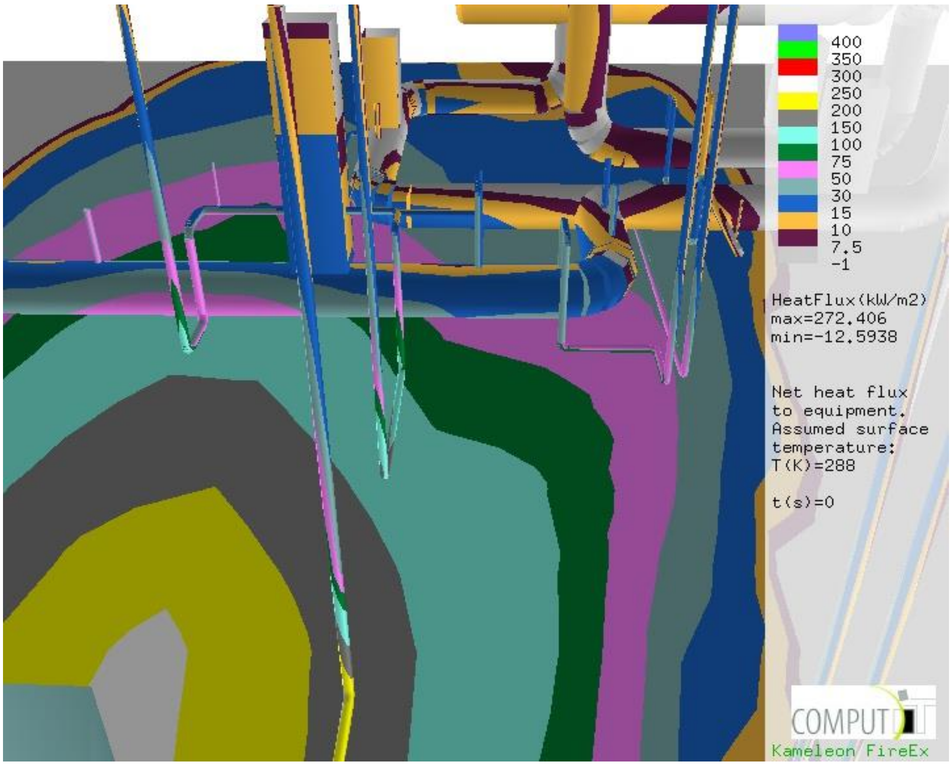
Time: 303 s, release flow: 4 kg/s



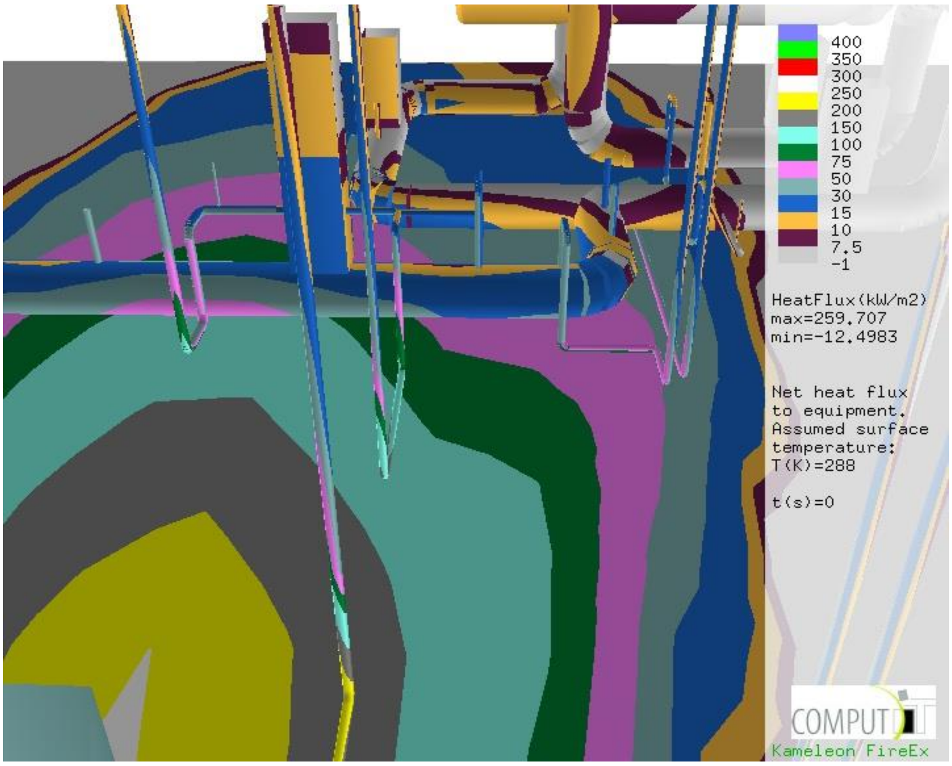
Time: 309 s, release flow: 3.76 kg/s



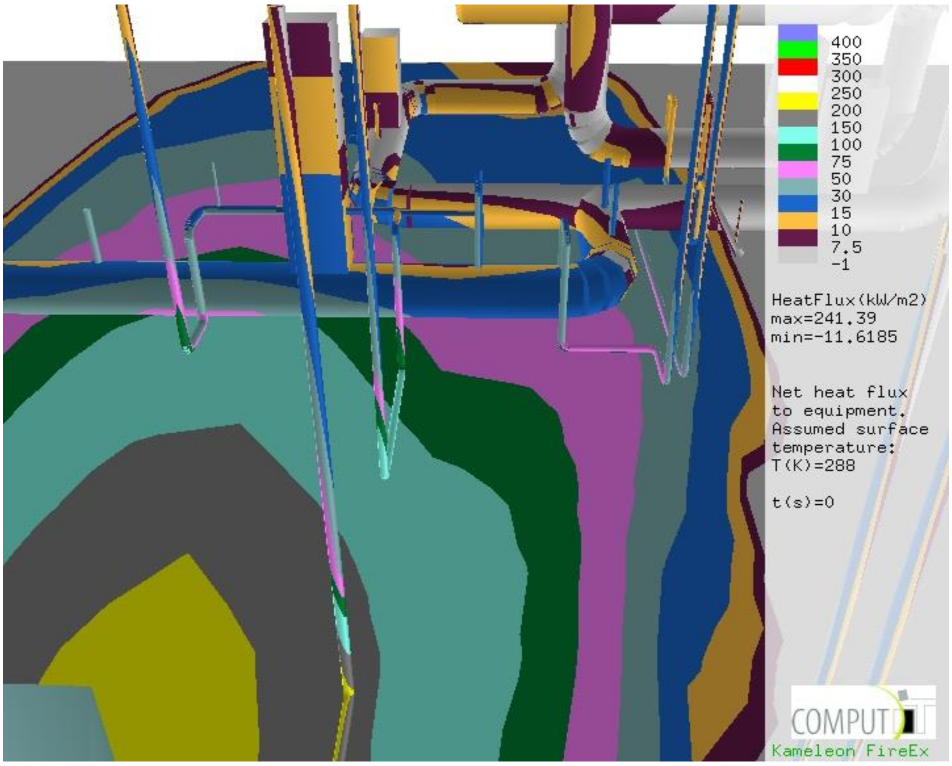
Time: 315 s, release flow: 3.53 kg/s



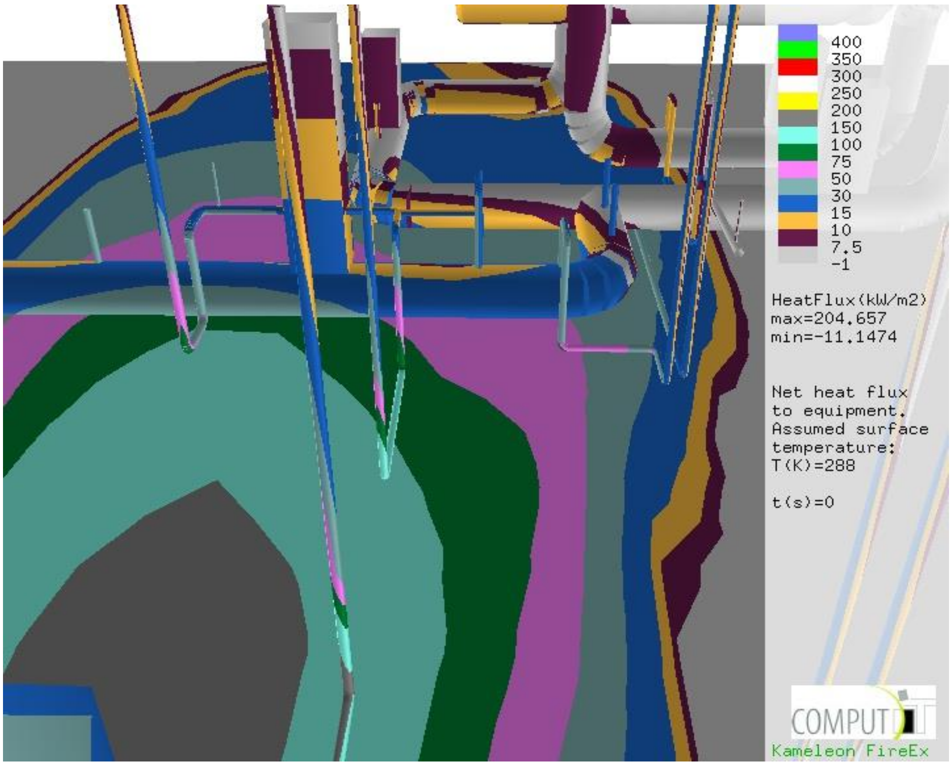
Time: 321 s, release flow: 3.32 kg/s



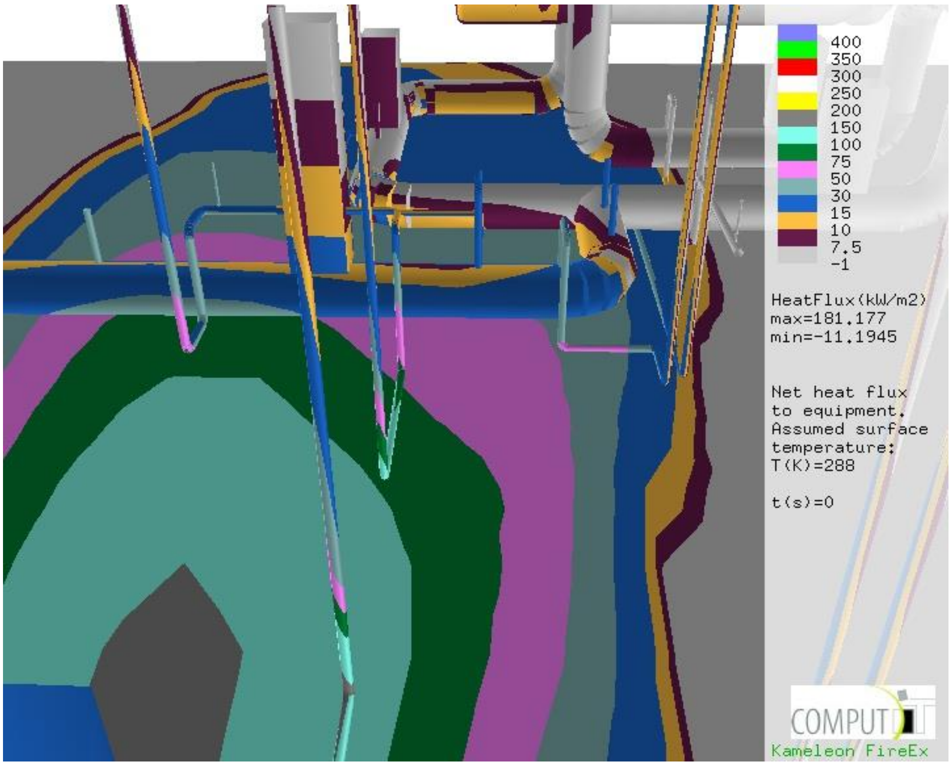
Time: 327 s, release flow: 3.13 kg/s



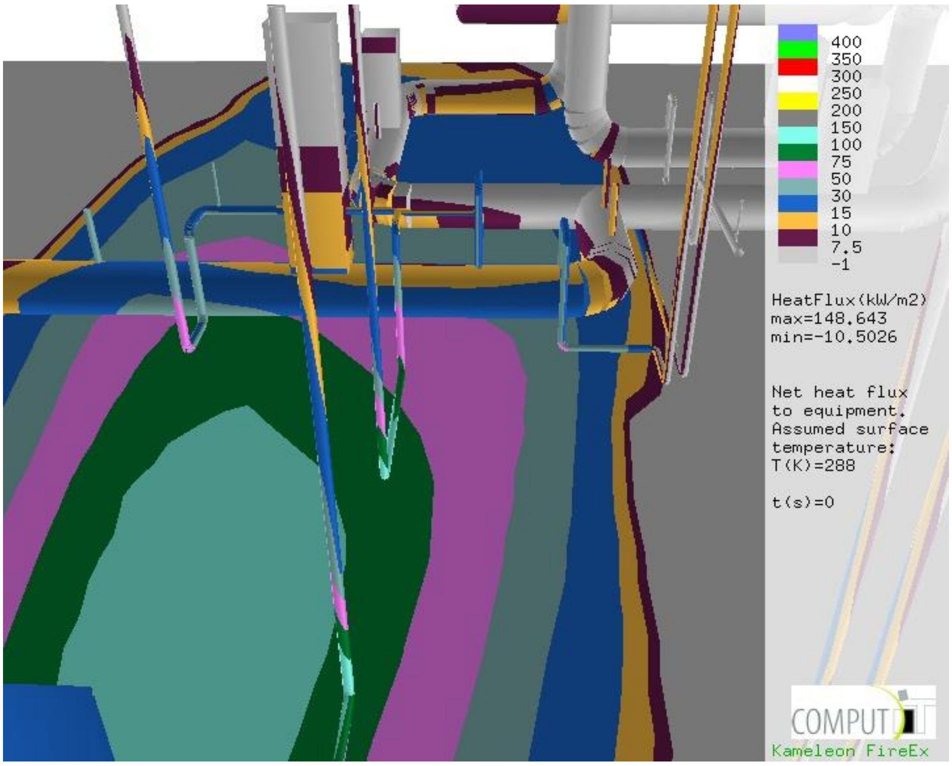
Time: 333 s, release flow: 2.95 kg/s



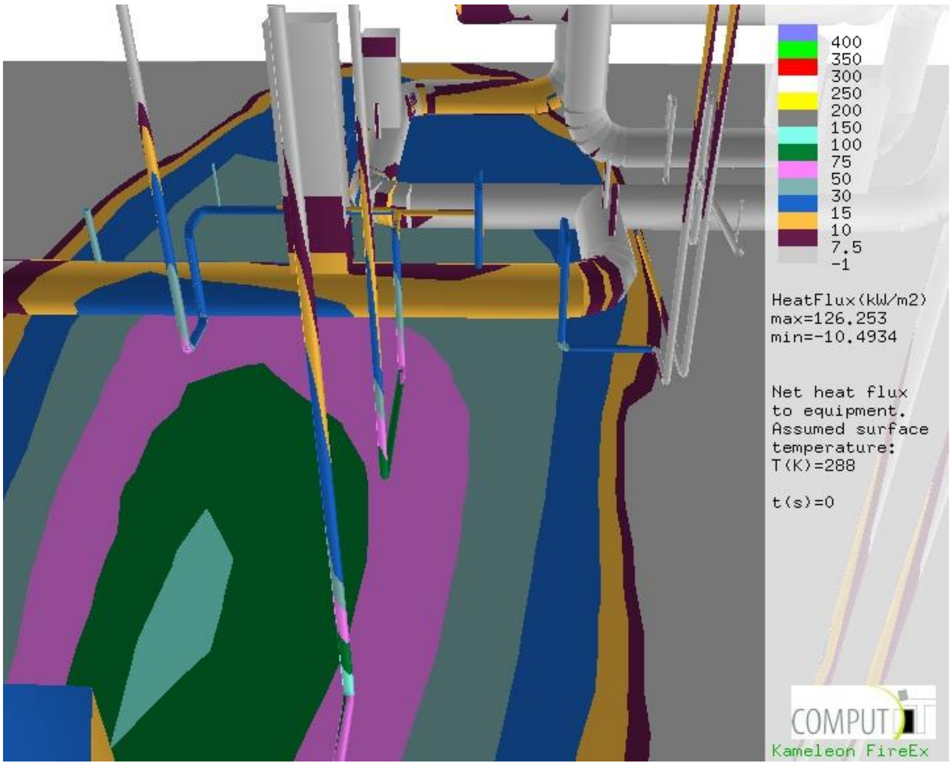
Time: 339 s, release flow: 2.78 kg/s



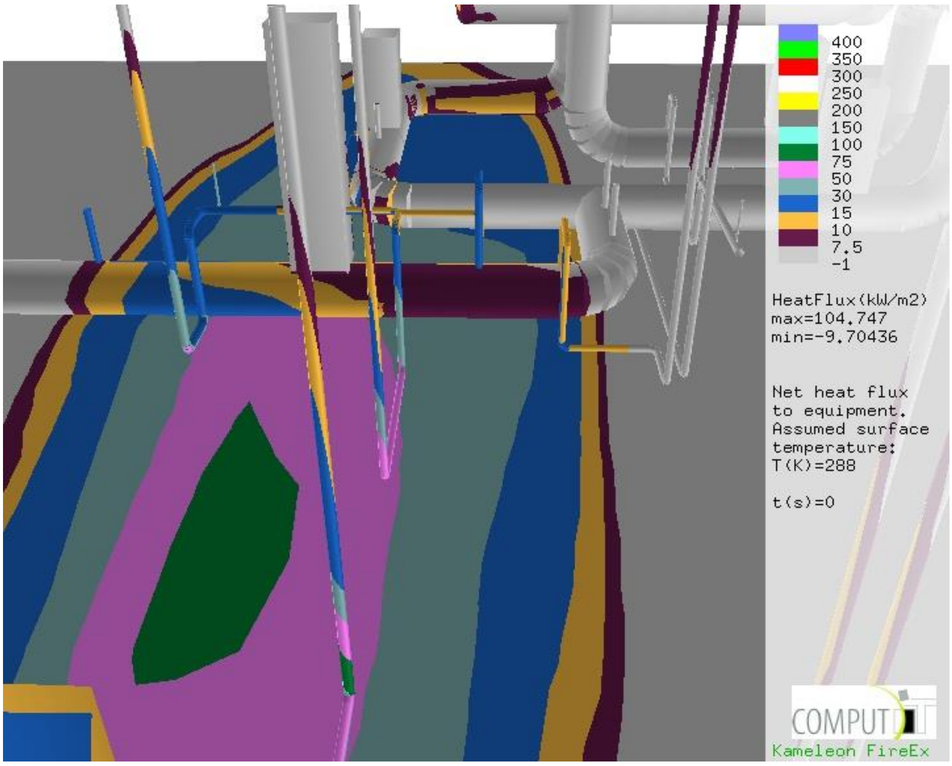
Time: 345 s, release flow: 2.63 kg/s



Time: 351 s, release flow: 2.48 kg/s



Time: 357 s, release flow: 2.33 kg/s



Time: 363 s, release flow: 2.19 kg/s

Appendix C. TNO yellow book leak calculation.

Leak profiles (inlcuding effect of blowdown)

Author: Jerome Renoult | Version: 1.1 | Date: 17/03/2005 | New version including accumulated volume of gas and cloud radius

General

Gas type	METHANE=84.2,ETHANE=6.4,PROPANE=4.8,BUTANE=4.6	
Mole weight	18,1	kg/kmol
Heat ratio (Cp/Cv)	1,296	-

Legend:
Input values
Calculated values

Reservoir			**Atmospheric**	
Pressure	126	bara	Pressure	1
Temperature	273,15	K	Temperature	293,15
Mass	4016,8	kg	Gas density	0,743
Critical pressure	1,854	bara		

Formulas:
P/P0=(M/M0)^gamma
T/T0=(M/M0)^(gamma-1)
rho=P/(Rgas*T)
Sub flow=SQRT(2/(gamma-1)*((gamma+1)/2)^((gamma+1)/(gamma-1))*(Pa/P)^(2/gamma)*(1-(Pa/P)^((gamma-1)/gamma)))
R=Cd*A*SQRT(rho*P*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)))

Nozzle			**Flammability**		
Diameter	0,013	m	LFL	5,0	%
Discharge coefficient	0,62	-	Stoichiometry	9,8	%
			UFL	15,0	%

Atm

Pressure	1,01325	bara

Blowdown

Diameter	0,0068	m
Discharge coefficient	0,62	-
Start time	0	s

								Accumulated volume of gas (m3)				Cloud radius (m)		
Time	Leak rate (kg/s)	Mass (kg)	Pressure (bara	Temperature (K	Sub-critical outflow	lowdown rate (kg/	Accumulated gas (kg)	All gas	At LFL	At stoichiome	At UFL	At LFL	At stoichiome	At UFL
0	1,951	4017	126,00	273,15	-	0,534	2,0	2,6	52,5	26,8	17,5	2,3	1,9	1,6
1	1,950	4014	125,90	273,10	-	0,533	3,9	5,3	105,1	53,6	35,0	2,9	2,3	2,0
2	1,948	4012	125,80	273,05	-	0,533	5,8	7,9	157,5	80,4	52,5	3,4	2,7	2,3
3	1,947	4009	125,70	273,00	-	0,533	7,8	10,5	210,0	107,1	70,0	3,7	2,9	2,6
4	1,946	4007	125,60	272,95	-	0,532	9,7	13,1	262,4	133,9	87,5	4,0	3,2	2,8
5	1,944	4004	125,50	272,90	-	0,532	11,7	15,7	314,7	160,6	104,9	4,2	3,4	2,9
6	1,943	4002	125,40	272,85	-	0,532	13,6	18,4	367,1	187,3	122,4	4,4	3,5	3,1
7	1,941	3999	125,29	272,80	-	0,531	15,6	21,0	419,3	213,9	139,8	4,6	3,7	3,2
8	1,940	3997	125,19	272,75	-	0,531	17,5	23,6	471,6	240,6	157,2	4,8	3,9	3,3
9	1,939	3994	125,09	272,70	-	0,530	19,4	26,2	523,8	267,2	174,6	5,0	4,0	3,5
10	1,937	3992	124,99	272,65	-	0,530	21,4	28,8	576,0	293,9	192,0	5,2	4,1	3,6
11	1,936	3990	124,89	272,60	-	0,530	23,3	31,4	628,1	320,5	209,4	5,3	4,2	3,7
12	1,935	3987	124,79	272,55	-	0,529	25,3	34,0	680,2	347,1	226,7	5,5	4,4	3,8
13	1,933	3985	124,69	272,50	-	0,529	27,2	36,6	732,3	373,6	244,1	5,6	4,5	3,9
14	1,932	3982	124,59	272,45	-	0,529	29,1	39,2	784,3	400,2	261,4	5,7	4,6	4,0
15	1,930	3980	124,49	272,40	-	0,528	31,1	41,8	836,3	426,7	278,8	5,8	4,7	4,1
16	1,929	3977	124,39	272,35	-	0,528	33,0	44,4	888,3	453,2	296,1	6,0	4,8	4,1
17	1,928	3975	124,29	272,30	-	0,527	34,9	47,0	940,2	479,7	313,4	6,1	4,9	4,2
18	1,926	3972	124,20	272,25	-	0,527	36,8	49,6	992,1	506,2	330,7	6,2	4,9	4,3
19	1,925	3970	124,10	272,20	-	0,527	38,8	52,2	1043,9	532,6	348,0	6,3	5,0	4,4
20	1,924	3967	124,00	272,15	-	0,526	40,7	54,8	1095,7	559,0	365,2	6,4	5,1	4,4
21	1,922	3965	123,90	272,10	-	0,526	42,6	57,4	1147,5	585,5	382,5	6,5	5,2	4,5

Author: Jerome Renoult	
General	
Gas type	METHANE=84,2,ETHANE=6,4,PROPANE=4,8,BUTANE=4,6
Mole weight	18,1
Heat ratio (Cp/Cv)	1,296
Reservoir	
Pressure	126
Temperature	=273,15
Mass	4016,8
Critical pressure	=((gamma+1)/2)^(gamma/(gamma-1))*B21
Nozzle	
Diameter	0,013
Discharge coefficient	0,62
Atm	
Pressure	1,01325
Blowdown	
Diameter	0,0068
Discharge coefficient	0,62
Start time	0

Time	**Leak rate (kg/s)**
0	=HVIS(D29>=Pa;HVIS(D29>=Pcritical;Cd*PI()*d^2/4*ROT(F29*D29*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G29*Cd*PI()*d^2/4*ROT(F29*D29*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A29+1	=HVIS(D30>=Pa;HVIS(D30>=Pcritical;Cd*PI()*d^2/4*ROT(F30*D30*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G30*Cd*PI()*d^2/4*ROT(F30*D30*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A30+1	=HVIS(D31>=Pa;HVIS(D31>=Pcritical;Cd*PI()*d^2/4*ROT(F31*D31*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G31*Cd*PI()*d^2/4*ROT(F31*D31*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A31+1	=HVIS(D32>=Pa;HVIS(D32>=Pcritical;Cd*PI()*d^2/4*ROT(F32*D32*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G32*Cd*PI()*d^2/4*ROT(F32*D32*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A32+1	=HVIS(D33>=Pa;HVIS(D33>=Pcritical;Cd*PI()*d^2/4*ROT(F33*D33*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G33*Cd*PI()*d^2/4*ROT(F33*D33*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A33+1	=HVIS(D34>=Pa;HVIS(D34>=Pcritical;Cd*PI()*d^2/4*ROT(F34*D34*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G34*Cd*PI()*d^2/4*ROT(F34*D34*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A34+1	=HVIS(D35>=Pa;HVIS(D35>=Pcritical;Cd*PI()*d^2/4*ROT(F35*D35*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G35*Cd*PI()*d^2/4*ROT(F35*D35*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A35+1	=HVIS(D36>=Pa;HVIS(D36>=Pcritical;Cd*PI()*d^2/4*ROT(F36*D36*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G36*Cd*PI()*d^2/4*ROT(F36*D36*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")
=A36+1	=HVIS(D37>=Pa;HVIS(D37>=Pcritical;Cd*PI()*d^2/4*ROT(F37*D37*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1)));G37*Cd*PI()*d^2/4*ROT(F37*D37*100000*gamma*(2/(gamma+1))^((gamma+1)/(gamma-1))));"")